
A new tool for hillslope hydrologists: spatially distributed groundwater level and soilwater content measured using electromagnetic induction

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Abstract:

New methods for obtaining and quantifying spatially distributed subsurface moisture are a high research priority in process hydrology. We use simple linear regression analyses to compare terrain electrical conductivity measurements (EC) derived from multiple electromagnetic induction (EMI) frequencies to a distributed grid of water-table depth and soil-moisture measurements in a highly instrumented 50 by 50 m hillslope in Putnam County, New York. Two null hypotheses were tested: $H_{0(1)}$, there is no relationship between water table depth and EC; $H_{0(2)}$, there is no relationship between soil moisture levels and EC. We reject both these hypotheses. Regression analysis indicates that EC measurements from the low frequency EM31 meter with a vertical dipole orientation could explain over 80% of the variation in water-table depth across the test hillslope. Despite zeroing and sensitivity problems encountered with the high frequency EM38, EC measurements could explain over 70% of the gravimetrically determined soil-moisture variance. The use of simple moisture retrieval algorithms, which combined EC measurements from the EM31 and EM38 meters in both their vertical and horizontal orientations, helped increase the r^2 coefficients slightly. This first hillslope hydrological analysis of EMI technology in this way suggests that it may be a promising method for the collection of a large number of distributed soilwater and groundwater depth measurements with a reasonable degree of accuracy. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS electromagnetic induction; soil water; groundwater; non-invasive; hillslope hydrology

INTRODUCTION

The issue of spatially distributed measurements for testing, development, calibration and validation of spatially distributed models is fundamental to the further progression of hydrology as a science (Beven, 2001). In non-forested areas, remote sensing techniques offer the ability to quantify internal state variables in a spatially distributed manner (Tansey *et al.*, 1999). However, in forested terrain, most of the techniques available are limited to ground-based measurements of groundwater and soil water owing to vegetation interference with space and airborne electromagnetic signals. Notwithstanding, knowledge of catchment soil and groundwater levels is needed to constrain the parameter space of even simple distributed models (Beven and Freer, 2001).

Currently, there are very few ways to obtain distributed subsurface moisture data. Jones *et al.* (2002) review the state of the art of time-domain reflectometry technology. Although mobile soil moisture measurement technologies exist, all are invasive and integrate over a very small area and volume. Distributed groundwater measurement technology suffers from a similar highly localized measurement problem. Recent studies have reported the control of topographic position on soil moisture (Western *et al.*, 1999) and groundwater levels (Siebert *et al.*, 2002). However, the predictive power of spatially explicit terrain measures often decreases as soil moisture decreases (Grayson and Western, 2001) or because of groundwater variations

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resulting from heterogeneities in the subsurface media (Nyberg, 1996). Thus, although topographic position is sometimes a useful tool for distributing point data in space, its predictive power is often weak and equivocal given its second-order control. Clearly, what is needed are new, direct measures of subsurface moisture at scales comparable to the pixelated catchment being modelled. This paper explores the use of electromagnetic induction (EMI) as a tool for the direct measurement of spatially distributed water-table and soil-moisture levels.

Electromagnetic induction has been demonstrated as a useful tool for mineral exploration (Irvine *et al.*, 1985), assessing and mapping soilwater salinity (Hendrickx *et al.*, 1992) and identifying contaminated groundwater plumes (Sweeney, 1984). Kachanoski *et al.* (1988) suggested that 'it should be possible to infer spatial variations in soil water content' using EMI techniques. Although promising, their data suggested that spatial variations in soil properties could limit the application of EMI across variable terrains. Encouraged by their findings though, we set out to quantify the relationship between terrain electrical conductivity (EC) and spatial measurements of water table depth and soil moisture at an intensively instrumented hillslope in Putnam County, New York. In this paper, we apply EMI data collected from two (high and low frequency) electromagnetic induction meters to a distributed grid of water table depth and soil moisture measurements and test the following null hypotheses.

H₀₍₁₎: there is no relationship between water-table depth and terrain electrical conductivity.

H₀₍₂₎: there is no relationship between soil moisture levels and terrain electrical conductivity.

To our knowledge, this is the first study to compare measurements of EC from multiple EMI frequencies to a distributed grid of water table and soil moisture measurements at the hillslope scale.

STUDY SITE

A 50 by 50 m plot was established around a residential septic field in Putnam County, New York (Figure 1) as part of a larger investigation of groundwater flow and transport (see Sherlock *et al.*, 2002). Depth to the water table below the leachate distribution lines ranges from 2 to 3 m, depending upon the time of year. At any given time, water-table depth is also highly variable across the hillslope. Groundwater is shallowest in the north-western zone, and deepest in the north-eastern zone of the study site, closely following the shape of the bedrock topography (Curry, 1999). Depth to bedrock is also highly variable and ranges from about 2 m in the south-east zone, to over 6 m in the north-east zone of the study site (Figure 1). These depths were identified from dynamic cone penetrometer and ground-penetrating radar field surveys. The soils at the site are Charlton loams (a coarse-loamy, mixed, mesic Typic Dystrochrept), which have formed from a stratified glacial drift deposit. The septic field is abandoned pastureland, with shallow slopes ranging from 2° to 8°. Average annual rainfall is 1160 mm. Rainstorms are often intense, resulting in rapid changes in near-surface soil moisture conditions (Sherlock *et al.*, 2002).

METHODOLOGY

The study site was instrumented previously to identify the dominant flow pathways and physical controls on septic effluent migration at the hillslope scale (Sherlock *et al.*, 2002). Hydrometric, water tracing and geophysical techniques were used to achieve this goal. In this paper, we focus on EMI data collected during the geophysical investigations and compare these data with soil moisture content and water table depth data collected during hydrometric investigations.

An EMI survey grid was established across the plot, consisting of 116 fixed survey points, spaced every 5 m across the plot (Figure 1). Electrical conductivity was measured at each survey point using the Geonics[®] EM31 and EM38 electromagnetic induction meters. The high-frequency (14.6 kHz) EM38 measures EC over

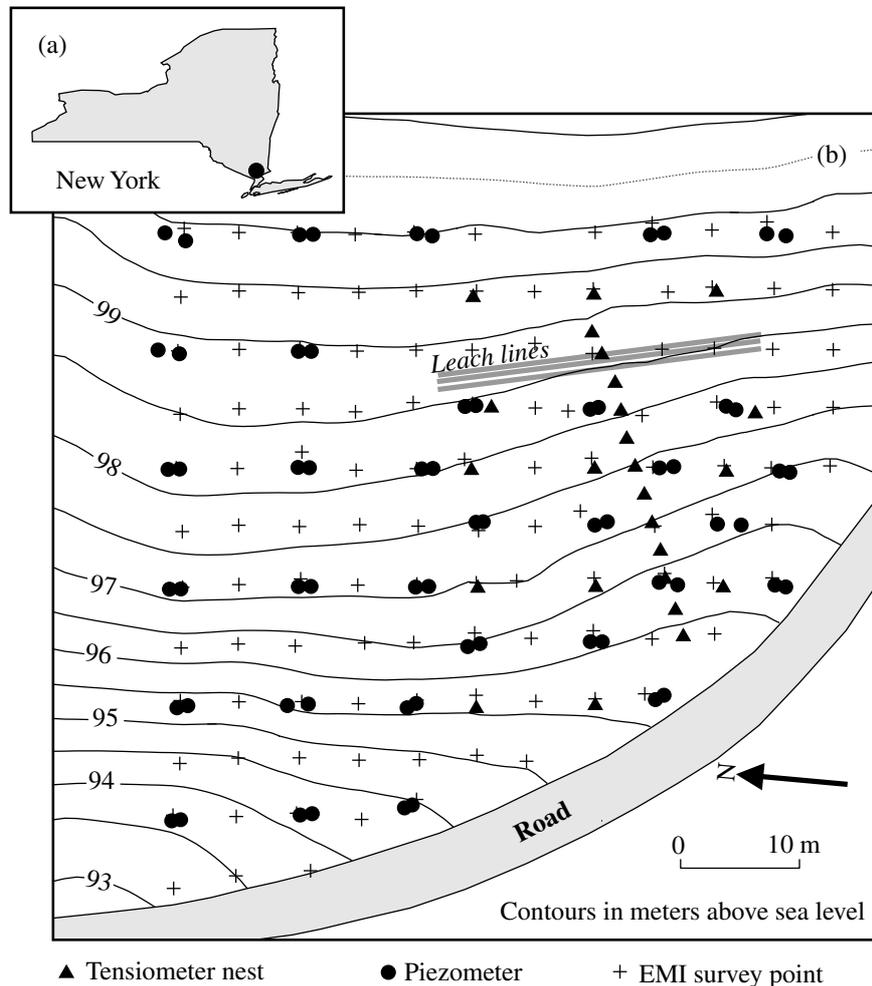


Figure 1. Location of instrumentation at the study site

a depth of approximately 0.75 m and 1.5 m when placed in the horizontal and vertical dipole orientations, respectively. The low frequency (9.8 kHz) EM31 measures EC over a depth of up to 3 m and 6 m in the horizontal and vertical dipole orientations, respectively. Theoretically, the depth of penetration has no limit, and measured EC at the ground surface is dependent on the electrical properties of the soil layers and soil moisture (McNeill, 1980). In this paper we define the above penetration depths as the *effective* penetration depths of the EM31 and EM38 meters.

Seven EMI surveys were conducted between 22 September 1998 and 10 November 1998, over a range of soil wetness conditions, but not during rainstorms. Electrical conductivity was measured using the EM38 and EM31 meters in both the vertical (EC_v) and horizontal (EC_h) orientations at each point on the survey grid. Occasionally, the EMI surveys were incomplete because of rainstorm activity during a survey. Of the 116 EMI survey points, 32 were located within 1 m of a piezometer nest, and 19 were located within 1 m of a tensiometer nest. The tensiometer and piezometer networks were installed previously as part of the hydrometric investigation of the septic field (Sherlock *et al.*, 2002). We use the EC data collected from these EMI survey points to compare with measurements of soil-moisture content and water-table depth derived from the co-located instrument clusters.

Spatially distributed measurements of soil-moisture content (θ) were derived from the network of tensiometer nests installed across the hillslope (Figure 1). Field-determined moisture-release curves were used to derive θ from measurements of matric potential (h) at 10, 50 and 130 cm depth. Matric potential was recorded across the hillslope either just prior to, or immediately following, the EMI surveys. On one occasion, a number of undisturbed soil cores were extracted randomly from a 20 cm depth across the hillslope for gravimetric (direct) determination of θ . Prior to core extraction, EC was measured at each sample location using the EM38 in the horizontal and vertical dipole orientations.

The piezometer clusters were used to estimate the water-table depth (d_{app}) at the time of each EMI survey. Unless dry, hydraulic head measurements from the shallowest piezometer with standing water of each cluster were used. The shallow piezometers were installed to about 1 m below the water table across the hillslope and screened over a 30 cm depth interval. Given that the EMI surveys were conducted during dry weather conditions, and that there were no hydrologically confining layers in either the lower vadose or upper phreatic zones (Sherlock *et al.*, 2002), the piezometric head measurements should give a close estimate of d_{app} .

RESULTS

Figures 2 and 3 illustrate the relationship between d_{app} and predicted water-table depth (d_{pred}) from the EC measurements for each field survey date. Linear regressions of d_{app} against EC measurements using the EM31 (Figure 2) and EM38 (Figure 3) meters in the vertical (EC_v) and horizontal (EC_h) dipole orientations, were used to make the spatially distributed water-table depth predictions.

Water-table depth predictions using the EM31 meter

On all survey dates, a very strong relationship was found between the EM31 EC_v and EC_h measurements and d_{app} (r^2 coefficients ranging between 0.61 and 0.82). Hence, there was good agreement between d_{app} and d_{pred} across the study site. However, we found consistently that EM31 EC_v measurements could be used to predict water-table depth with a slightly greater degree of certainty than the EC_h measurements (compare r^2 coefficients in Figure 2). The difference probably results from the different penetration depths of the horizontal and vertical dipole orientations. Below a depth of about 3 m, deeper water-table levels were not matched by decreases in EC_h as was apparent at other zones of the hillslope where the water table was shallower. As the use of the EM31 in the horizontal dipole orientation permits a penetration depth of only about 3 m, EC_h measurements will not reflect changes in groundwater status below this depth. Thus, the relationship between EC_v and d_{app} is better maintained than that between EC_h and d_{app} at water-table depths greater than 3 m. There was very little difference in the strength of the relationship between d_{app} and EC_v or EC_h , where the water table was less than 3 m deep. The vertically orientated EM31 meter was, therefore, a better predictor of water table depth over the 1 to 6 m range.

However, the relationship between EC_v or EC_h measurements and d_{app} shifted from one survey date to the next. This is demonstrated by the shifts in the linear regression trend lines over time (Figure 4). This presents a problem for the prediction of water-table depth from EC measurements based upon a calibration of EC and d_{app} determined on a previous survey date. Reasons for this non-stationarity are explored in the discussion of this paper, although clearly this issue has an impact on the accuracy of water-table depth predictions over repeat surveys.

EM38 response versus water-table depth

Predictions of water-table depth from linear regression equations of d_{app} against EM38 measurements of EC_v and EC_h exhibited much greater uncertainty than the predictions using the EM31 EC measurements (see r^2 coefficients in Figure 3). Again, EC_v measurements consistently predicted the water-table depth with greater certainty than the EC_h measurements. However, given that the EM38 has a typical effective penetration

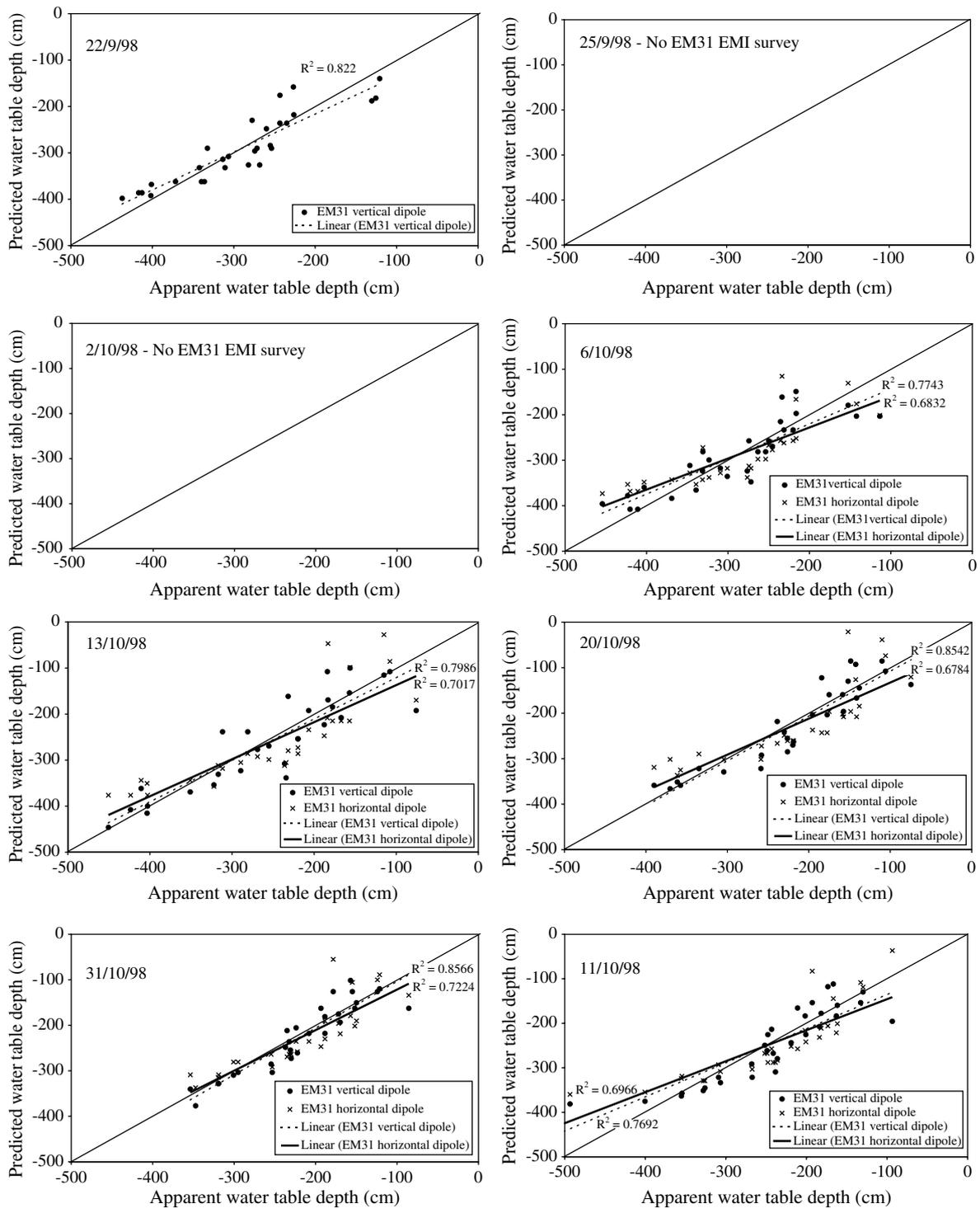


Figure 2. Predicted water-table depth versus apparent water-table depth using the vertical and horizontal dipole orientations of the EM31 meter

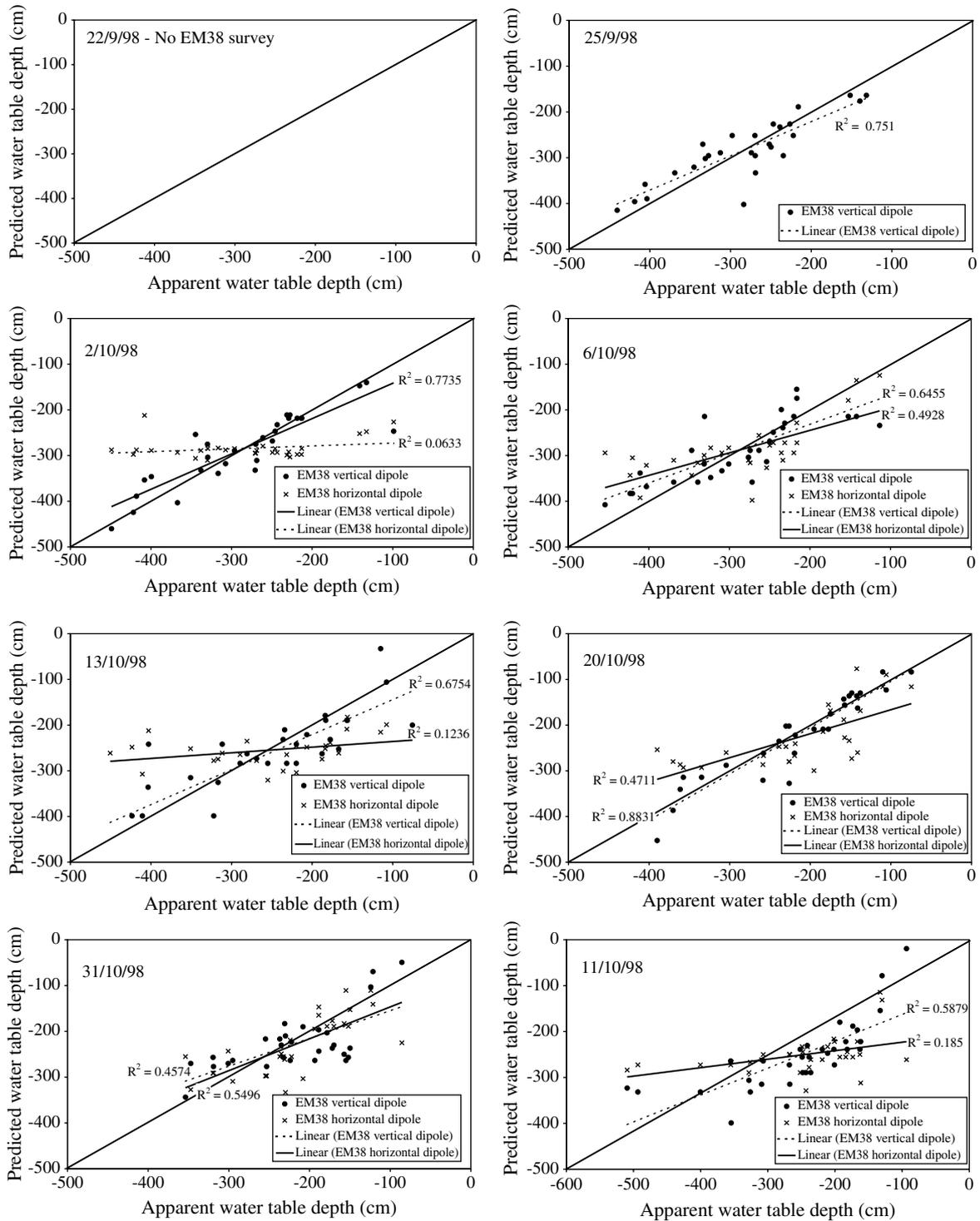


Figure 3. Predicted water-table depth versus apparent water-table depth using the vertical and horizontal dipole orientations of the EM38 meter

depth of 1.5 m, the d_{pred} values do not reflect the relationships between EC and d_{app} . Rather, the relationships shown are a result of the fact that the near-surface soil moisture levels tend to co-vary with water-table depth (i.e. where the water table is deep, near-surface soil moisture levels tend to be lower, assuming dry antecedent conditions, and vice versa). Therefore, the magnitude of the EM38 EC measurements were probably related more to variations in soil moisture levels within the upper vadose zone across the hillslope. We examine the relationship between EM38 response and soil moisture levels in a later section of this paper.

Use of simple moisture retrieval algorithms

Given the potential of EC measurements in the prediction of water-table depth, we devised simple retrieval algorithms (based on what others have done in the remote sensing field with passive microwave data (e.g. Neale *et al.*, 1990)), combining both the EC_v and EC_h data from the EM31 and EM38 meters. Manipulations of the EC data sets were examined to see if the predictive potential of EC measurements could be improved further. Table I indicates that simple manipulations of the high (EM38) and low (EM31) frequency EC_v and EC_h data could be used to predict water-table depth with greater certainty. Combining the low and high frequency EC_v data was most successful, producing r^2 coefficients as high as 0.86.

The removal of three outlying data points from the analysis resulted in even higher r^2 coefficients (Table II). This removal is justified because (i) one EMI survey location in the north-west corner of the study site had a very high EC, which could be explained by very high sodium concentrations measured in the groundwater at this locality, and (ii) two of the EMI survey locations were sited directly over the septic distribution lines, resulting in much greater EC measurements, given the local soil water status. For example, when the high and low frequency EC_v data were combined (i.e. using the $(31v + 38v)/2$ retrieval algorithm) and regressed against d_{app} , the r^2 coefficient was 0.91 for the 20 October 1998 EMI survey.

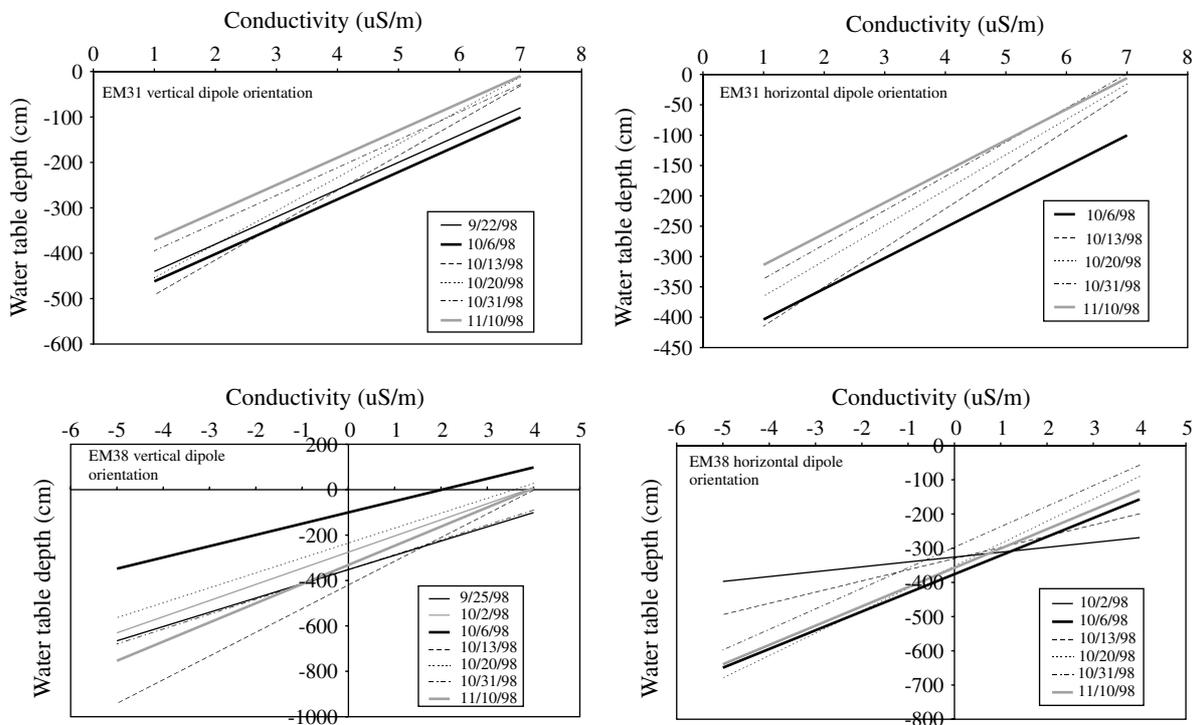


Figure 4. Least squares linear regression trend lines of EC against d_{app}

Table I. r^2 correlation coefficients of d_{app} against d_{pred} using simple manipulations of the EM31 and EM38 derived EC_v and EC_h data sets

Survey date (1998)	EMI meter and dipole orientation				Retrieval algorithm	
	31v	31h	38v	38h	(31v + 31h)/2	(31v + 38v)/2
6 October	0.77	0.68	0.65	0.49	0.76	0.73
13 October	0.80	0.68	0.63	0.12	0.79	0.80
20 October	0.81	0.61	0.84	0.37	0.75	0.85
31 October	0.82	0.68	0.53	0.51	0.78	0.86
10 November	0.77	0.70	0.59	0.19	0.80	0.80

31v = EM31 EC_v measurements; 31h = EM31 EC_h measurements; 38v = EM38 EC_v measurements; 38h = EM38 EC_h measurements.

Table II. r^2 correlation coefficients of d_{app} against d_{pred} using manipulations of the EM31 and EM38 derived EC_v and EC_h data sets with the outliers from the north-west corner of the study site removed from the analysis (owing to elevated sodium concentration levels in the groundwater)

Survey date (1998)	EMI meter and dipole orientation				Retrieval algorithm	
	31v	31h	38v	38h	(31v + 31h)/2	(31v + 38v)/2
13 October	0.80	0.70	0.68	0.12	0.80	0.83
20 October	0.85	0.68	0.88	0.47	0.82	0.91
31 October	0.86	0.72	0.46	0.55	0.83	0.89
10 November	0.79	0.76	0.69	0.19	0.86	0.88

31v = EM31 EC_v measurements; 31h = EM31 EC_h measurements; 38v = EM38 EC_v measurements; 38h = EM38 EC_h measurements.

EM38 response versus soil moisture content

The EC_v and EC_h measurements derived from the EM38 meter were regressed against (i) 33 gravimetric measurements of soil moisture, determined on intact soil cores extracted from 20 cm depth, and (ii) apparent soil-moisture content derived from moisture-release conversion of the h data at 10, 50 and 130 cm depth at the study site.

The strength of the EM38 EC_v and EC_h relationship with direct (gravimetric) soil-moisture content (θ) measurements at 20 cm depth was encouraging (r^2 of 0.60 and 0.70 respectively; Figure 5). Presumably, the EC_h correlation with θ was stronger because of the shallow effective penetration depth of the EM38 horizontal dipole orientation (0.75 m) relative to the vertical orientation (1.5 m). However, by combining the EC_v and EC_h data, the certainty with which EC could be used to predict θ , increased slightly (Figure 6). Given the destructive and time-consuming nature of the core extraction approach for gravimetric moisture determination, EC data from the EM38 meter were compared only with direct measurements of θ on one survey date. Therefore, we could not test the robustness of this relationship over time.

Simple linear regression of the raw EC data set on θ at 10, 50 and 130 cm depth (estimated from moisture-release conversion of the h data) suggested a very poor relationship between the two variables (r^2 ranging between 0.01 and 0.15). As already stated, two of the EMI survey locations were sited directly over the septic distribution lines, where effluent concentrations in the subsurface are greatest (Curry, 1999). After these two data points were removed from the analysis, linear regressions of the adjusted EC data on θ at 10, 50 and 130 cm identified positive relationships, although the strength of these relationships remained poor. These

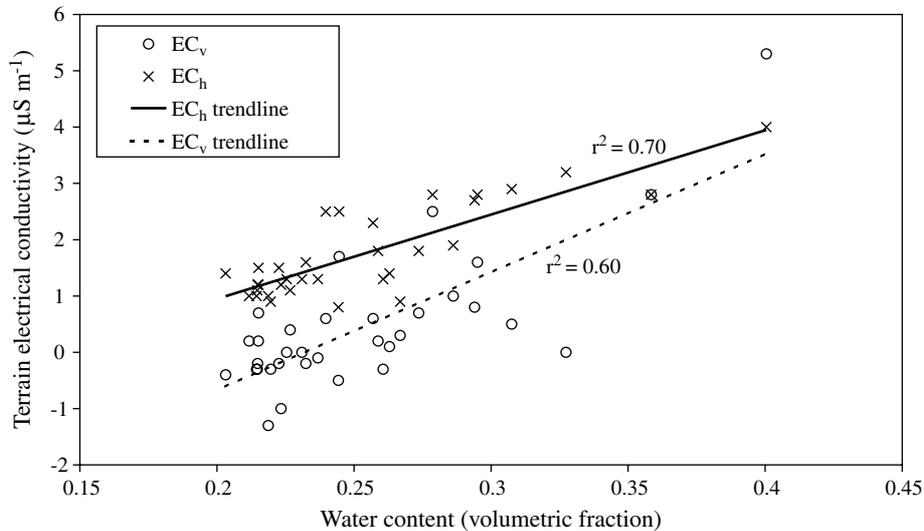


Figure 5. Terrain electrical conductivity versus gravimetrically determined soil-moisture content during the survey on the 5 October 1998

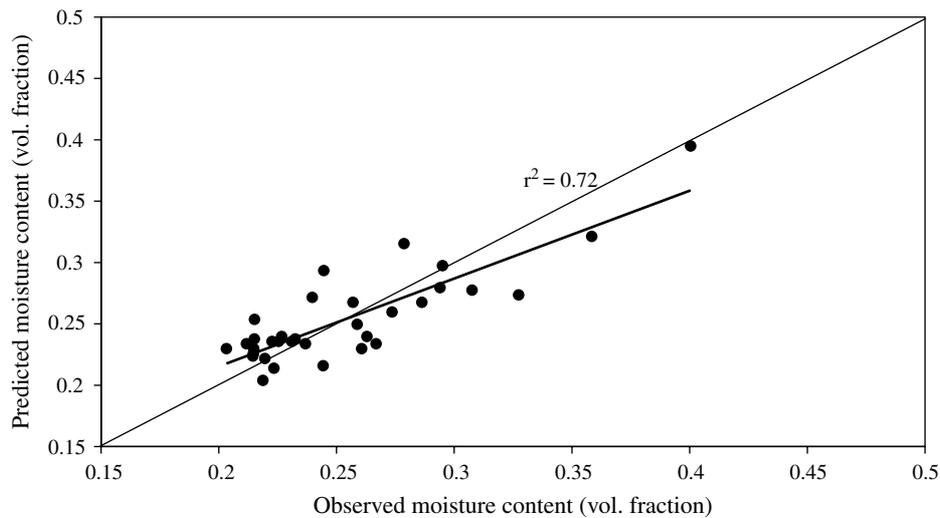


Figure 6. Predicted versus observed, gravimetrically determined soil-moisture content at 20 cm depth. Predictions based upon simple regression analysis of combined EM38-derived EC_v and EC_h measurements (using an averaging algorithm) against observed soil-moisture content

regression equations were used to plot θ_{pred} against θ_{app} for the 13 October 1998 EMI survey in Figure 7, which clearly illustrates that θ_{pred} based upon EM38 EC measurements was poor.

The strength of the θ (determined using the gravimetric approach) versus EC relationship relative to the θ (determined using h measurements) versus EC relationship, merits comment. Spatial measurements of θ based upon moisture-release conversion of the h data are prone to error, because the shape of a moisture-release curve for a given depth typically exhibits a large amount of variability across field soils. In the present study, the moisture-release function was determined in the field at a single locality (Figure 1), but was used to derive θ from h across the whole field. Thus, the moisture-release function may be erroneous for many of the tensiometer nests, resulting in erroneous estimates of soil-moisture content. Furthermore, as with the

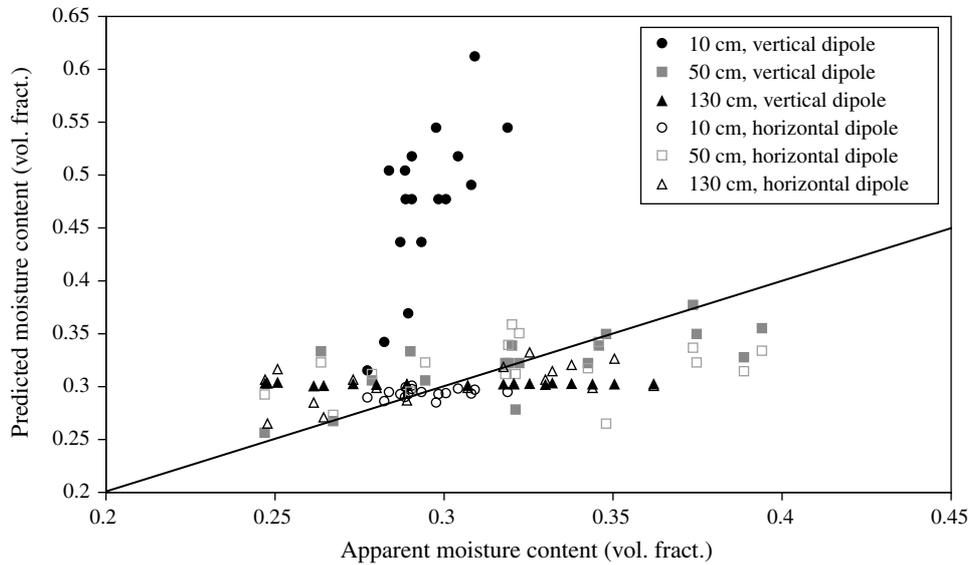


Figure 7. Predicted versus apparent moisture content at 10, 50 and 130 cm depth, derived from moisture-release conversion of the matric potential data. Predictions based upon simple regression analysis of EM38-derived EC_v and EC_h against apparent soil moisture content

relationship between EM31 derived EC measurements and d_{app} , the form of the relationship between EM38 derived EC and θ_{app} changed between survey dates. Thus, near-surface soil moisture content predictions based upon a predetermined calibration of EC and θ will be highly uncertain.

DISCUSSION

Usefulness of EMI to subsurface moisture mapping

The results of this study indicate that the EM31 and EM38 meters are potentially useful tools for the rapid mapping of groundwater levels and near-surface soil moisture status, respectively. The sometimes noisy relationship of d_{pred} against d_{app} and θ_{pred} against θ_{app} indicates that factors other than soil moisture content and water table depth exert second-order effects on the measurement of EC using the EM31 and EM38 meters. These effects have been discussed in detail previously (e.g. Hendrickx *et al.*, 1992), and is currently the subject of active research. We conducted our EMI surveys in and around a residential septic field. As such, solute concentrations in the soil and groundwater exhibited significant spatial variability (Curry, 1999). Solute concentration anomalies resulted in elevated EC measurements at three of the EMI survey stations. Smaller concentrations at other locations across the field will have affected the EC measurements to unknown degrees. Indeed, the area where EMI technology has been most widely used to date has been in the mapping of subsurface contamination plumes. A key feature of this hillslope, as revealed by subsurface sampling and ground-penetrating radar investigations, is the high variability of bedrock depth across the hillslope (Sherlock *et al.*, 2002). Although the soil properties were relatively uniform across the hillslope, the variable bedrock depth will affect, to some degree, the EC measurements. However, in spite of the bedrock depth variability and our rather *contaminated* hillslope, strong relationships emerged between EM31 EC measurements and water-table depth, and EM38 EC measurements and soil-moisture content. We consider this study site to be a 'worst case scenario' from a hillslope hydrologist's perspective, and that our data imply that moisture status in the subsurface exerts the first-order control on EC. These results are therefore highly encouraging, and bode well for the use of EMI techniques to map soil and groundwater status in pristine forest catchment environments.

Potential problems

Although a positive relationship was always identified between EMI response and groundwater proximity/soilwater status, the form of the relationship changed over time (Figure 4). A linear regression ($r^2 = 0.77$) was determined between EM31-derived EC_v and d_{app} on the 6 October 1998 (Table I). When this regression equation was used to predict water-table depth from EC_v measurements taken during subsequent field surveys, the error in d_{pred} increased with time after the 6 October 1998 survey (Figure 8). For example, five weeks after the 6 October 1998 survey, d_{pred} was over 1 m deeper than d_{app} in some areas of the hillslope (see $d_{pred} - d_{app}$ distributions on 10 November 1998 in Figure 8). The change of the EM31 response to a given water-table depth may result from a gradual drift in the instrument circuitry, or perhaps other external factors such as decreasing temperature of soil and soil water through the autumn season.

During our field investigations, we noted that EC_h measurements using the EM38 meter were highly sensitive to the local placement of the instrument during each EMI survey. A slight change in the positioning of the meter could alter the EC_h measurement by as much as 2 $\mu S/m$. Furthermore, on several of the survey dates, a number of 'negative' EC measurements were observed using the EM38 meter (see Figure 5). Negative measurements of terrain conductivity are not physically possible. This indicates that the unit was not correctly zeroed prior to each survey, or that the response of the unit drifted during usage. The sensitivity of the EM38 measurements to zeroing and local placement could explain some of the EM38 response shift. Recently, new generation EMI meters have incorporated circuitry to remove signal drift during instrument usage (e.g. the Geonics® GEM-300, Won *et al.*, 1996). Presumably such instruments will also exhibit little drift between surveys, which bodes well for the future use and accuracy of EM-derived moisture content and groundwater-level data.

Future research needs

Use of retrieval algorithms, which combine the vertical and horizontal EMI response, resulted in slightly better predictions of both groundwater depth and soil moisture status. Presumably, this results from the depth integration effects of combining different penetration depths. Although quite rudimentary, similar retrieval algorithms have been used for years in the remote sensing field (see Neale *et al.*, 1990). We perceive this to be a way to begin to define distribution functions of moisture with depth using EMI techniques. As the depth of exploration is determined primarily by the measurement frequency, an instrument capable of logging several EMI frequencies simultaneously has the potential for estimating a distribution function of wetness with depth. Such instruments may reveal subsurface properties, which may have not been identified by a single-frequency instrument. The use and application of multifrequency EMI techniques in subsurface hydrological studies requires further investigation. Moisture retrieval algorithms incorporating several measurement frequencies also could be developed to enhance predictions of soil moisture and water-table depths in the subsurface.

These results clearly demonstrate the potential of EMI techniques for obtaining a large number of soilwater and water-table depth measurements non-invasively at the hillslope scale under land cover not suitable for airborne remote sensing techniques. Although the slope of the relationship between EC and d_{app} changed from survey to survey, these results also demonstrate the potential for rapid repeat EMI surveys making either 'point' measurements at gridded positions across the landscape or in a continuous record mode as the operator traverses the catchment. The application of this technology could help resolve the issue of spatially distributed measurements of soilwater and groundwater, which are critical for the calibration and validation of physically based distributed hydrological models. Recently, new approaches to incorporate soft data into catchment model calibration exercises (Siebert and McDonnell, 2002) have been proposed. At this stage, we view EMI as a potential fuzzy classification measure for subsurface water content distribution at the headwater catchment scale.

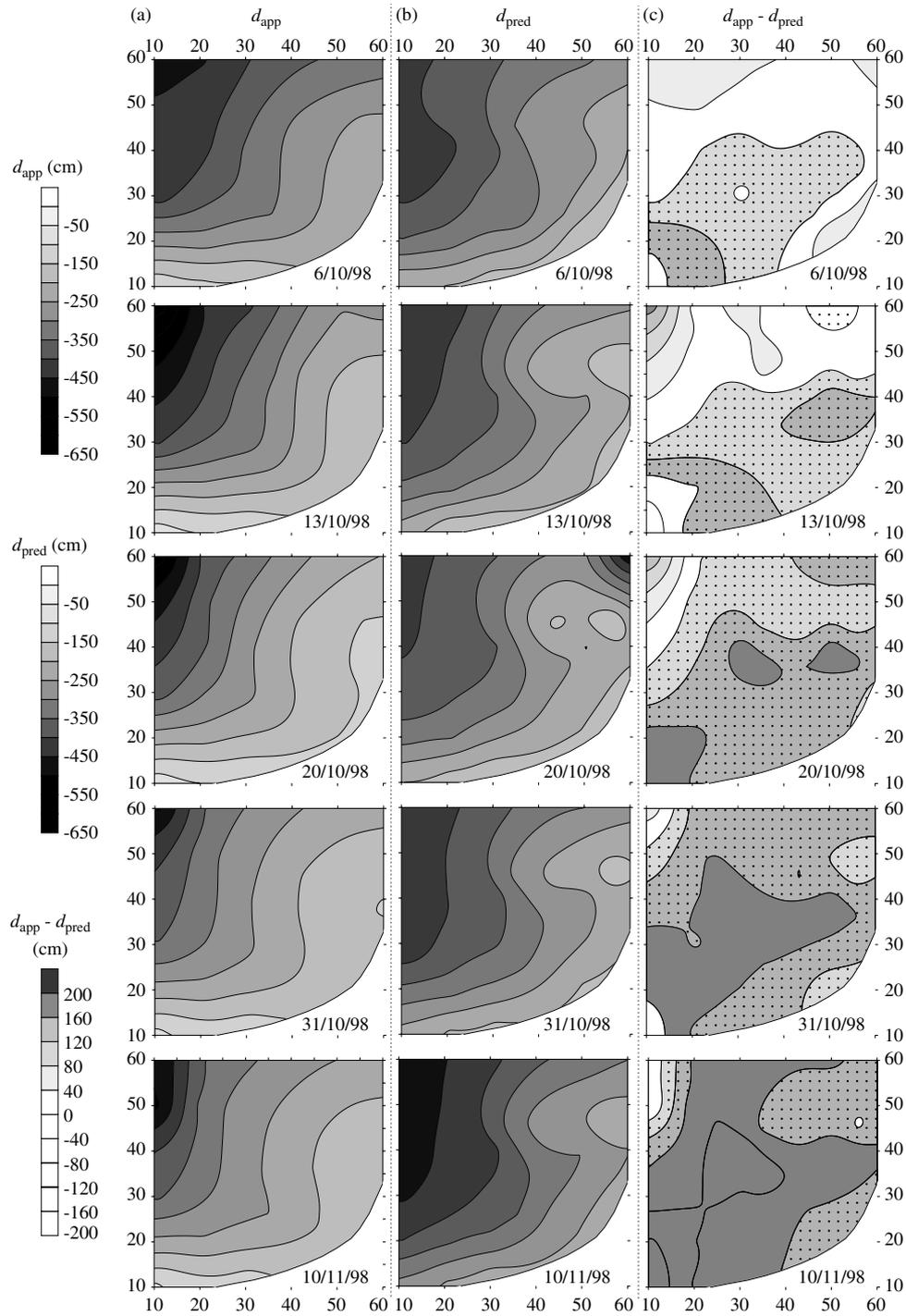


Figure 8. Hillslope distributions of (a) Measured water-table depth, (b) predicted water-table depth, and (c) the difference between measured and predicted water-table depth on five EM survey dates. Water-table depth predictions for all dates are based upon a linear regression of water-table depth and EM31 EC_v measurements on the 6 December 1998. Dotted areas indicate that the measured water-table depth was shallower than the predicted water table depth

CONCLUSIONS

This study tested two null hypotheses: $H_{0(1)}$, there is no relationship between water-table depth and terrain electrical conductivity; $H_{0(2)}$, there is no relationship between soil moisture levels and terrain electrical conductivity. We reject both of these hypotheses. Measurements of EC_v using the EM31 meter could, on most survey dates, explain over 80% of the variation in water table depth. Despite the zeroing problems encountered with the EM38 meter, the higher frequency EC measurements could explain over 70% of the soil-moisture variance in the upper 20 cm. The use of simple retrieval algorithms helped increase the r^2 coefficients slightly. The EMI approach offers the potential for the collection of a large number of distributed soilwater and water-table depth measurements with a reasonable degree of accuracy. Further work should incorporate multifrequency data sets, to help resolve some of the uncertainty issues associated with this non-contacting technology. We are also exploring the use of EMI during storm events for examining water flowpaths during wetting and drying.

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