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Full Length Research Paper

Soil depth inferred from electromagnetic induction measurements

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There is a need for rapid cost effective methods to obtain spatially distributed data of soil depth. Soil depth determines the subsurface topography, a major control on the distribution of flowpaths in landscapes. An EM38 survey was conducted on a 12 ha site at Bloemfontein, South Africa. A significant linear relationship between soil depth and EC_a were obtained with multiple linear regression (Soil depth = 149 - 29 $CV_{0.5}$ + 34 CV_1). It was found that the equation can reasonably accurately (RMdAE = 20%, REF = 0.49) estimate soil depth from EC_a readings. This made it possible to estimate 15,000 soil depths across the study area, which contributed to the successful characterization of subsurface topography. Consequently the following conclusions could be made. There was a close correlation between surface and subsurface topography. Overland flow seems to be high causing erosion on higher elevations and deposition of sediments and accumulation of water in lower lying areas. From flow accumulation maps, sites possibly controlling the hydrology of the study area were identified. The methodology developed should contribute towards characterising hydrological research sites.

Key words: EM38, soil depth, soil water, hydrological response, thresholds, water flow.

INTRODUCTION

Hillslopes are considered fundamental landscape elements and the smallest entity for a holistic study of hydrological processes. The hydrological response of watersheds depends on responses of individual hillslopes in the watershed (Sivapalan, 2003a; Weiler and McDonnell, 2004). The complexity of hydrologicaln processes, driven by heterogeneities in landscape characteristics, diminishes the applicability of hillslopes as basic elements for watershed models. It was therefore argued that instead of focussing on unconventional behaviour of different hillslopes one should search for common threads, concepts and patterns in the hydrological response of hillslopes, to be able to intercompare hillslopes from various regions, geologies, with different soils and vegetation (Sivapalan, 2003a, b; McDonnell et al., 2007).

The threshold response of hillslopes to precipitation is proposed as a unifying concept of how hillslopes function and a suitable tool for intercomparisons of subsurface processes between hillslopes (Tromp-van Meerveld and McDonnell, 2006a). These thresholds might be the formation of a saturated wedge at the discharge face, expanding upslope (Weyman, 1973); threshold pre-event water contents, favouring the generation of macropore flow (Uchida et al., 2005); groundwater ridging (Sklash and Farvolden, 1979) and/or saturated excess overland flow, that is, variable source areas (Dunne and Black, 1970); and more recently, the connectivity of the hillslope in terms of transient saturation. Isolated patches of saturation should first be connected before significant subsurface flows are generated (Tromp-van Meerveld and McDonnell, 2006b; Lexartza-Artza and Wainwright, 2009; Hopp and McDonnell, 2009). The *'fill and spill'* hypothesis was suggested by Tromp-van Meerveld et al. (2006b), where depressions in the bedrock topography ought to be 'filled' first before 'spilling' over

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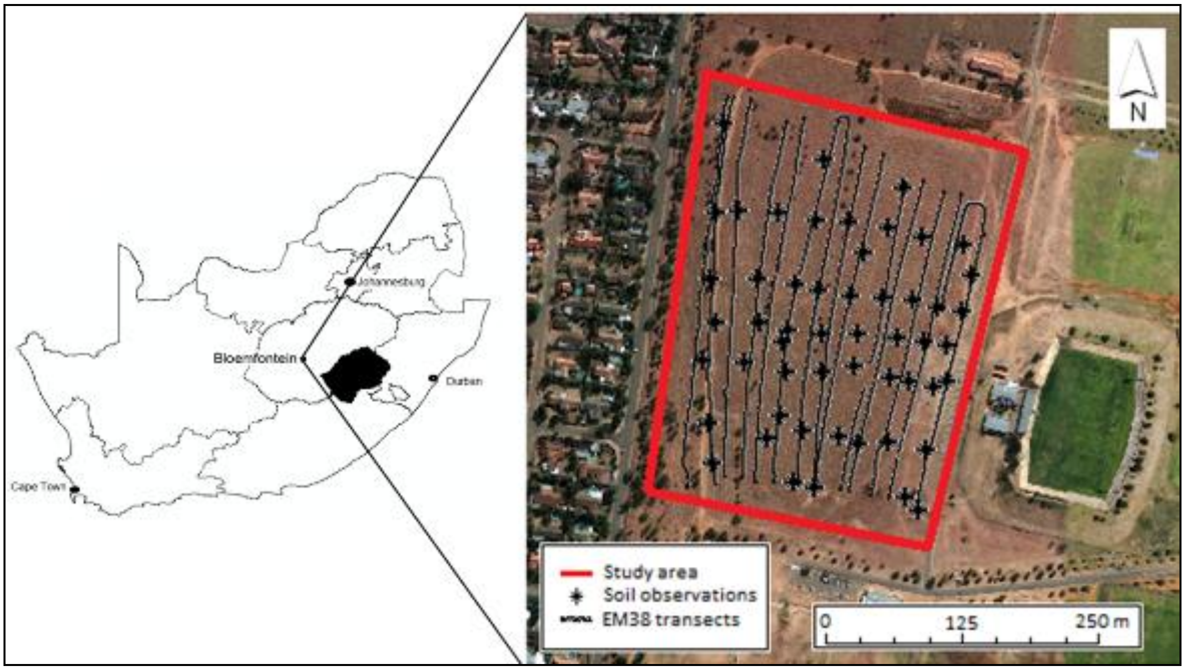

Figure 1. Location of study area, EM38 transects and soil depth observations.

microtopographic relief at the soil/bedrock interface, connecting subsurface saturated areas and increasing the generation of subsurface stormflow.

The spatial variability of flowpaths makes generalisation from transect data to hillslope scale a difficult task. Tromp-van Meerveld et al. (2006b) agreed that they probably would not have noticed ‘connectedness’ in their Panola hillslope if not for a detailed network of spatially distributed wells and detailed soil depth measurements. We agree that more measurements of the surface and subsurface lateral flow paths, water table fluctuations, connectivity of the various water bodies and the residence flow time of water through the landscape would be ideal for an enhanced understanding and modelling of the hydrological behaviour of hillslopes. Detailed spatial measurements are however only feasible on relatively small hillslopes (e.g. Panola is approximately 0.1 ha), but it becomes more expensive and impractical as the size of the study area increases. Electromagnetic induction (EMI) is a non-invasive, cost- and time efficient technique, able to produce large quantities of data about subsurface conditions. EMI have been used *inter alia* to estimate depth to clay layers (Doolittle et al., 1994), soil salinity (Hendrickx and Kachanoski, 2002), water table depths and soil water contents (Sherlock and McDonnell, 2003) and soil texture (Abdu et al., 2008). Indeed, geospatial measurement of apparent soil electrical conductivity (EC_a), generally applied in site specific crop management or precision agriculture, has become one of the most reliable and frequently used measurements to characterise soil variability. From the available sensors, the mobile non-invasive electromagnetic induction (EMI) Geonics EM38 and EM31 sensor is the most popular.

Since EC_a is influenced by everything in the soil that conducts an electrical induced current, EC_a survey data is focused toward ensuring that acquired EC_a data correlate with the specific soil variable. Differences in the conducting capacity of consolidated material and unweathered bedrock will influence EC_a measurements to such an extent that depths to soil/bedrock transitions can be determined.

The aim of this study was firstly to assess whether EMI data can be used to predict soil depth and secondly to determine the subsurface topography and to advocate the applicability and importance of EMI interpretations in hydrological studies.

STUDY AREA AND METHODOLOGY

An EM38 survey was conducted on an open area on the western part of the University of the Free State (UFS) campus, Bloemfontein, South Africa (Figure 1). The selected area is approximately 12 ha in size and receives an average rainfall of around 550 mm year^{-1}, predominantly in the form of high intensity thunder storms during the summer months that is November to March. The elevation ranges between 1440 and 1420 masl with very gentle slopes. Beaufort shales, mudstones and dolerite are the dominant geological formations in the area. The soils exhibit different degrees of weathering due to the variation in parent material and different water regimes, resulting in a variety of depths. Surface crusting resulting in overland flow is expected to govern the hydrological behaviour of the study site. Although the area is not located in a hydrological research site it was selected for this study due to its accessibility and because the soils are relatively shallow (<1500 mm), falling within the maximum effective reading depth of the EM38.

Table 1. Statistical analysis of non-parametric quantile regression between measured soil depth and EC_a ($CV_{0.5}$ and CV_1).

Soil depth	Coefficient	Standard error	t	P>t
$CV_{0.5}$	-29.144	5.171	-5.640	0.000*
CV_1	34.495	3.923	8.790	0.000*
Constant	148.569	47.594	3.120	0.003*

*, Significance level of 0.01; **, significance level of 0.05.

The survey was done on the 13th of September 2011 following the dry winter months. A calibrated GeoNics EM38 was pulled behind a quad bike in north-south transects over the study area. EC_a measurements were taken on 1 s intervals totalling more than 15 000 readings. Two EC_a readings were taken simultaneously namely $CV_{0.5}$ (0.5 m between coils) and CV_1 (1 m between coils). The difference between the coils determines the effective reading depth, the smaller the distance, the shallower the reading depth. $CV_{0.5}$ and CV_1 are integrated conductivity values in mS m^{-1} over a depth of 0 to 750 and 0 to 1500 mm, respectively.

Soil depths were measured up to the bedrock with a 1 m cone-penetrometer. Refusal that is soil/bedrock interface was defined as the depth where 5 blows with a 4.6 kg hammer did not result in a 1 cm downward movement of the penetrometer. For the soils deeper than 1 m, the soils were hand-augured to the bedrock, and the depths recorded. A total of 65 soil depth observations, spread over the study area, were made (Figure 1).

To test for a linear relationship between measured soil depth (dependent variable) and EC_a ($CV_{0.5}$ and CV_1, two independent variables) a multiple linear regression was done. EC_a and soil depth measurements were not normally distributed. Transformation of the data did result in a normal distribution of EC_a measurements, but was unsuccessful for soil depth measurements. For this reason it was decided to use non-parametric quantile regression. This method estimates the median (not mean) of the soil depth measurements (dependent), conditional on the values of the EC_a measurements (independent). The method finds a line through the data that minimizes the sum of absolute residuals. The EC_a measurement closest to the measured observation was used in the regression.

From the function that was developed, soil depths were calculated for surveyed transects. These depths were then interpolated using the inverse distance weighted (IDW) technique and a soil depth map was created for the study site. Surface elevations were also obtained from the EM survey and a Digital Elevation Model (DEM) was created. Soil depth and surface elevation rasters were converted to point layers, spatially joined based and the difference between the surface elevation and the soil depth is equal to the subsurface elevation; for which another DEM was created. To infer surface and subsurface flowpaths, flow accumulation rasters were created where a stream channel has more than 350 cells draining into it. These flowpaths are considered to be important localities for measuring surface and subsurface hydrological processes. ArcMap™ 10.1 (ESRI, 2012) software was used for all the GIS related operations.

RESULTS AND DISCUSSION

Relationship between soil depth and EC_a

The results of the regression between measured soil depth and EC_a ($CV_{0.5}$ and CV_1) are presented in Table 1. Satisfactorily was the fact that there was a significant relationship (y=149-29x+34x) between soil depth and EC_a.

Additionally, the proportion of variation in soil depth, that could be estimated by knowing the EC_a and the coefficients for the equation of the line, was high (R^2 = 0.53).

To evaluate the accuracy of the equation, estimations of soil depth from EC_a measurements were compared against measured soil depths (Figure 2). The relative median absolute error (RMdAE) shows that there was a 20% over- and/or under-estimation of soil depth by the function. The estimated soil depths compared well to the median of the measurements, with a relative modelling efficiency (EF) of 0.49. A value below 0 would have meant that the median measured soil depth would have been a better estimator than the function, which was not the case here. The quantile regression of measured soil depth versus estimated soil depth, showed that the slope (0.94) and intercept (23) did not differ significantly from 1 and 0, respectively, which are good indicators of accuracy (Bellocchi et al., 2010). Unfortunately the reliability of the function could not be assessed, due to the fact that an independent data set (a data set other than the one used to develop the function) was required. This was however beyond the scope of this paper. Thus, it can be concluded that there is a significant linear relationship between soil depth and EC_a, which can be used to estimate soil depth in the study area, with reasonably accuracy, from the 15 000 EC_a readings. Because no reliability asessment could be completed, the authors are under no illusion that the equation is a universal soil depth estimation equation for EM38 measurements. Variations in soil conditions (e.g. salt and water content) will modify the conducting capacity of the soil, and consequently alter the calibration equation, possibly decrease or the accuracy.

Soil depth and surface topography

The interpolated soil depths are presented in Figure 3a. The majority of the soils are shallower than 800 mm; isolated pockets of deeper soils can clearly be identified. In general, the soil depth follows the surface evaluation inversely, that is, deeper soils are found at lower elevations (Figure 3b). The inverse relationship between soil depth and surface elevation is presented in Figure 4.

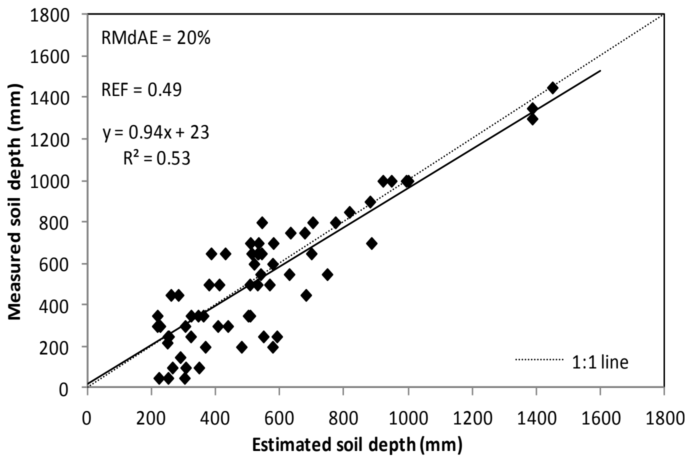

Figure 2. Measured soil depths vs. soil depths estimated from EC_a measurements.

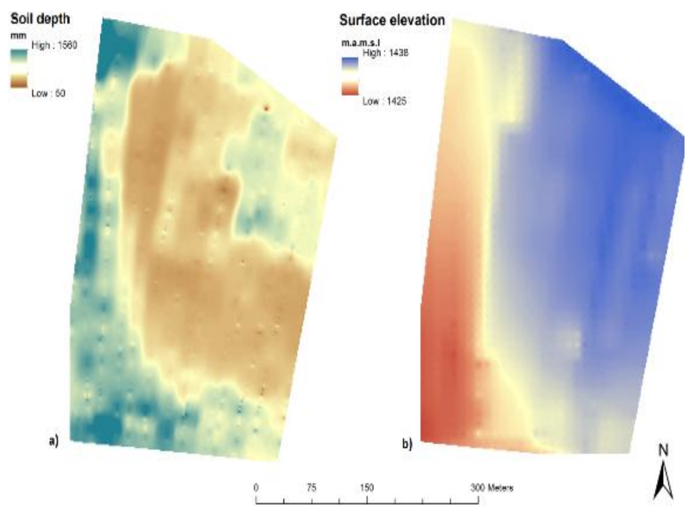

Figure 3. (a) Soil depths as calculated from regression (Table 1) and interpolated from measured transects and (b) surface elevation, also interpolated from surveyed transects.

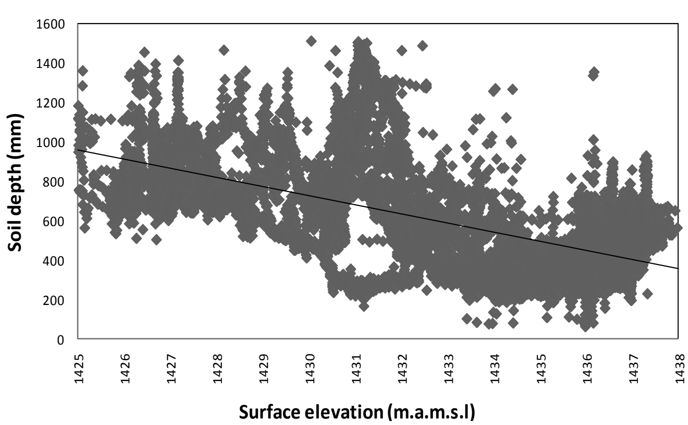

Figure 4. Relationship between soil depth and surface elevation.

The isolated pockets of deeper soils which are visible in Figure 3a can be observed as peaks in Figure 4 that is deep soils at relatively high elevations. The correlation between surface and subsurface topography and therefore soil depth, can be attributed to hydrological controlled soil genesis. Overland flow is an important flowpath controlled by surface topography where higher elevations are eroded. Limited infiltration results in less weathering and the combination of these processes results in shallower soils on high elevations compared to soils of lower lying land where water and sediments accumulate. Accumulation of colloidal material and more chemical weathering due to increased water contents result in deeper soils present in the lower lying areas (Figure 3a and b).

Subsurface topography and flow accumulation

The inverse correlation between surface topography and soil depth results in similar trends between surface topography and subsurface topography. The subsurface topography (surface elevation – soil depth), follow the surface topography very closely in this study site (Figure 5). In semi-arid arid areas where overland flow and associated process (erosion and accumulation of water and sediments) are dominant, the subsurface topography will be amplified by the surface topography that is in lower lying surface elevation areas, soils will be deeper.

This interaction between surface and subsurface topography is explained in Figure 5, where the flow accumulation (cells) for the surface and subsurface topography respectively, were calculated. Figure 5 represents the number of cells contributing to a specific cell based on the location and the relative elevation of the cell in the study area. Note that Figure 4 does not represent all the points in the study area (>70,000). The maximum and minimum flow accumulation values were selected and then approximately 20,000 randomly selected locations. Lower lying cells would receive more water and result in a higher flow accumulation value and *vice versa*. One cell is approximately 1.6 m^2 in size. There is a very good correlation between the surface flow accumulation and the subsurface flow accumulation on a specific location in the study area (R^2 = 0.98 in Figure 5). This supports the visual interpretation of Figures 3a and b, stating that the surface topography controls the soil depth and thus the subsurface topography. The deviation of the trendline from the 1:1 line in Figure 5, indicates that there is more water accumulating in the lower lying areas of the subsurface topography than compared to that of the surface topography. The increase in soil depth with a decrease in the relative elevation, for the reasons given earlier, might be the reason for more cells contributing to specific areas in the subsurface topography.

The highest number of cells accumulating on a certain point is 21,160 and 18,832 for the subsurface and surface elevation layers, respectively. This represent 3.38

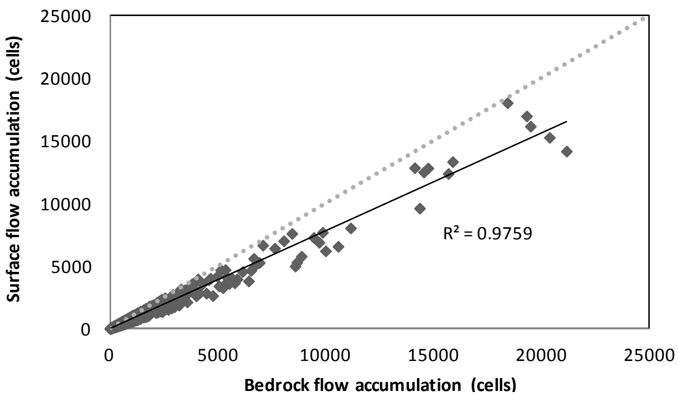

Figure 5. Flow accumulation calculated from surface and subsurface topography.

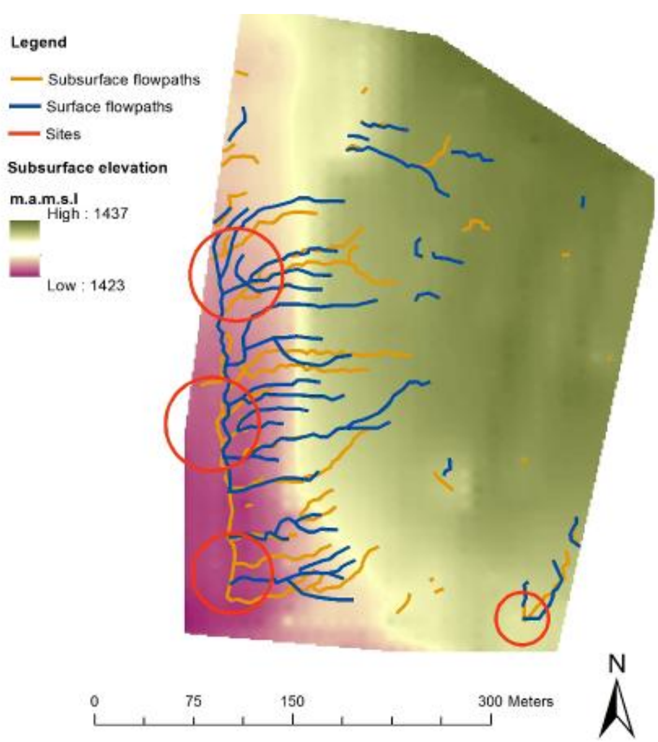

Figure 6. Subsurface elevation, subsurface and surface flowpaths and suggested research sites of the study area.

ha or 28% of the study area for the subsurface topography and 3 ha or 25% of the study area for the surface topography. The location of this high accumulation of cells is found in the south western (SW) corner of the study site (Figure 6). This area is marked by low elevation and deep soils. Figure 6 also higlightes the difference between surface and subsurface flowpaths (flow accumulation of more than 350 cells). Flowpaths of the surface topography are more connected and occur more frequently compared to that of the subsurface topography.

Suggested sites for future research and instrumentation

In Figure 6, four areas encircled in red, are suggested for further investigation, based on the origin and confluence of hydrological pathways. Although future research is unlikely on the selected site (it was only selected for the development of the methodology), we believe that these areas represent some of the key hydrological mechanisms occurring in the study area. In catchment and hillslope hydrological studies, the major aim is to quantify outflow in the form of streamflow exiting the catchment or the contribution of a hillslope to streamflow. It would be expensive and ultimately futile to study and instrument the entire area when flows are only generated on small portions. We believe that areas where flow pathways originate and converge are the important areas prompting the hillslope or catchment to respond hydrologically.

The traditional way of studying and instrumenting hillslopes in the form of transects perpendicular to the contours, might therefore not reflect the dominant control mechanisms of that hillslope. Also, inflection points in the surface topography are often identified as the ideal location for detailed investigation of hydrological processes. However, in areas with soils with high infiltration capacities (the majority of hydrological study sites), the subsurface topography controls the response of the hillslopes, and surface and subsurface topographies often do not correlate well. This might lead to incorrect selections of "representative" sites and therefore erroneous interpretations of the hydrological response of that hillslope.

Conclusions

A significant linear relationship (equation) between soil depth and EC_a were obtained with multiple linear regressions. Measured soil depths compared well (RMdAE = 20%, REF 0.49) to estimations made with the equation from EC_a measurements. Thus, the equation proved to be accurate, from where 15,000 soil depths could be estimated across the study area. This contributed to the successful characterization of subsurface topography, which made the following conclusions possible.

The soil depth of the study area shows a close inverse association with the surface topography, as is evident from visual interpretations and flow accumulation correlations. The reason for the close correlation between soil depth and surface topography can be attributed to overland flow following the surface topography removing soils from higher lying areas and deposition in lower lying areas. Flow accumulation maps indicate that accumulation of water in lower lying areas might result in a higher degree of weathering in the lower areas.

The flow accumulation maps, based on the subsurface topography, suggest that only small portions of the study area are involved in the generation of flow. These areas are important to investigate as they will ultimately determine the hydrological response of the study area.

We suggest that a 3-D survey of any research site should prelude any effort to instrument new research sites. These surveys will also improve interpretations on existing research sites. In this study inference of soil depths from EMI measurements proved to be a valuable, time and cost efficient contribution to the understanding of the hydrology of the research site.

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