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A case study on the use of appropriate surrogates for antecedent moisture conditions (AMCs)

G. A. Ali and A. G. Roy

Chaire de recherche du Canada en dynamique fluviale, Département de géographie,
Université de Montréal, C.P. 6128, Succursale Centre-ville, Montréal (QC) H3C 3J7, Canada

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Correspondence to: G. A. Ali (genevieve.ali@umontreal.ca)

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Abstract

While a large number of non-linear hillslope and catchment rainfall-runoff responses have been attributed to the temporal variability in antecedent moisture conditions (AMCs), two problems emerge: 1) the difficulty of measuring AMCs, and 2) the absence of explicit guidelines for the choice of surrogates or proxies for AMCs. This paper aims at determining whether or not multiple surrogates for AMCs should be used in order not to bias our understanding of a system hydrological behaviour. We worked in a small forested catchment, the Hermine, where soil moisture has been measured at 121 different locations at four depths on 16 occasions. Without making any assumption on active processes, we used various linear and nonlinear regression models to evaluate the point-scale temporal relations between actual soil moisture contents and selected meteorological-based surrogates for AMCs. We then mapped the nature of the "best fit" model to identify 1) spatial clusters of soil moisture monitoring sites whose hydrological behaviour was similar, and 2) potential topographic influences on these behaviours. Two conclusions stood out. Firstly, it was shown that the sole reference to AMCs indices traditionally used in catchment hydrology, namely antecedent rainfall amounts summed over periods of seven or ten days, would have led to an incomplete understanding of the Hermine catchment dynamics. Secondly, the relationships between point-scale soil moisture content and surrogates for AMCs were not spatially homogeneous, thus revealing a mosaic of linear and nonlinear catchment "active" and "contributing" sources whose location was often controlled by surface terrain attributes or the topography of a soil-confining layer interface. These results represent a step forward in developing a hydrological conceptual model for the Hermine catchment as they indicate depth-specific processes and spatially-variable triggering conditions. Further investigations are, however, necessary in order to derive general guidelines for the choice of the best surrogates for AMCs in a catchment.

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1 Introduction

A large number of non-linear hillslope and catchment rainfall-runoff responses have been documented around the world (e.g., Wipkey and Kirkby, 1978; Sidle et al., 1995; Buttle and Peters, 1997; Buttle et al., 2001; Van Meerveld and McDonnell, 2005; Tromp-Van Meerveld and McDonnell, 2006a; James and Roulet, 2007). Justification for such hydrological responses often lies in the temporal variability in storm size or antecedent moisture conditions (AMCs) (Longobardi et al., 2003; Mishra et al., 2005; James and Roulet, 2009) and the spatial connectivity between source areas. Soil moisture is a major control on catchment response. It is notably used to determine whether a catchment is in a dry and spatially disorganized or in a wet and connected state (Grayson et al., 1997). Catchment AMCs are most often associated with soil moisture contents over a fixed antecedent temporal window that can be defined as:

$$W = (t_0 - x, t_0) \tag{1}$$

Where t_0 is the reference time and x is the amount of time to be subtracted to account for conditions observed before the reference time. Hence, AMCs are used for various purposes, from computing direct surface runoff via the Soil Conservation Service Curve Number (SCS-CN) methodology (Mishra et al., 2005) to characterizing favourable conditions for hydrologic connectivity to occur (James and Roulet, 2009).

The determination of a catchment AMCs remains difficult given the relative scarcity of spatially-detailed soil moisture data in comparison to rainfall or streamflow data that are more accessible. Owing to these difficulties, several practical approaches have been proposed to define surrogates or proxies for AMCs. Precipitation-based indices have received the largest attention as rainfall data are often available (Longobardi et al., 2003). We here distinguish between antecedent precipitation (AP_x) and the antecedent precipitation index (API_n). AP_x is simply the cumulative sum of rainfall recorded over any fixed antecedent temporal window as defined in Eq. (1). The API_n as put forward by Kohler and Lindsey (1951) is rather a weighted summation of daily precipitation amounts recorded since the last rainfall as described in Eq. (2):

$$\mathrm{API}_n = \mathrm{API}_{n-1} + P_{n-1} \cdot \exp(-\alpha \Delta t) \tag{2}$$

Where $\Delta t = t_n - t_{n-1}$ is the time (d) elapsed between the end of the previous rainfall P_{n-1} and the beginning of the next one P_n, and α is a parameter equal to the inverse of the characteristic time of soil moisture depletion (d^{-1}). According to Kohler and Lindsey (1951), precipitation-based indices are universally applicable and yield good results provided that they are used in conjunction with season of the year or temperature. Basin evaporation (Longobardi et al., 2003) and the soil moisture index (SMI), which only includes potential evaporation and other climatic factors in its formulation (Mishra et al., 2005), have also been described as potential proxies for AMCs since they relate to soil moisture depletion. Given the findings that pre-event water can play a substantial role in rainfall-runoff response (e.g., Sklash and Farvolden, 1979; Pearce, 1990; Rice and Hornberger, 1998; Kirchner, 2003) and given the wide availability of streamflow data, the antecedent baseflow index (ABFI) (Mishra et al., 2005) and other measures related to discharge recorded just prior the reference time (Kohler and Lindsey, 1951; Longobardi et al., 2003) have been proposed as surrogates for AMCs. Kohler and Lindsey (1951) have advocated that baseflow-derived indices provide reasonably good results in humid and sub-humid regions; however, these indices are strongly dependent upon season of the year and do not necessarily reflect short-term changes in a catchment state. Several authors have emphasized the relative advantage of the ABFI in comparison to antecedent rainfall because it does not force the choice of an antecedent temporal window (Mishra et al., 2005) and it is a better predictor of runoff generation (Longobardi et al., 2003). Nonetheless, the ABFI is not often used in the hydrological literature (Mishra et al., 2005), with the exception of a few studies based on water table heights (e.g., James and Roulet, 2009). The number of days since the last rainfall event is another proxy for AMCs that is seldom used in catchment hydrology (Kohler and Lindsey, 1951)

Several questions arise concerning the selection of a proxy for AMCs for a specific catchment. For instance, with regards to antecedent precipitation, what duration of antecedent temporal window should be used? The term “antecedent” is broadly used in the literature and refers to durations from one hour to 30 days. Antecedent temporal windows of seven days (e.g., Woods and Rowe, 1996; Inamdar and Mitchell, 2007; James and Roulet, 2009) and ten days (e.g., Noguchi et al., 2001; Western et al., 2004) are relatively popular in catchment hydrology. Several studies have relied on the dual use of AP_{10} and AP_{30} (e.g., Sidle et al., 1995; Vidon et al., 2009). The curve number (CN) method considers rainfall over a 5-day long antecedent temporal window (SCS, 1956), an approach taken up by some hydrological modeling studies (e.g., Brocca et al., 2008). Silveira et al. (2000), however, compared the single use of 5-day antecedent rainfall with the combined use of 15-day antecedent rainfall and potential evaporation and found no significant differences between the two approaches. While working in a semi-arid environment, Frot and van Wesemael (2009) argued that the use of a 48-h long antecedent temporal window was not appropriate to explain the differences in runoff for events with similar precipitation characteristics and rather chose an antecedent period of 20 days. Within the antecedent window, several scenarios can occur as there may be no rainfall, a single rainfall event, or multiple storms. These events will or will not be accounted for depending on the chosen duration (Salvadori and De Michele, 2006). Thus, Seeger et al. (2004) used a large selection of antecedent windows (i.e. 6 h, 24 h, and 3, 7, 15 and 21 days) in order to discriminate the effects of short-term AMCs from those of long-term AMCs in a small headwater catchment. The wide range of antecedent temporal windows in the literature is unavoidable as there are no explicit guidelines available to specify the relations between soil moisture content and antecedent rainfall during a specific time period (Mishra et al., 2005). Moreover, the effectiveness of surrogate measures for AMCs may be highly dependent upon climate characteristics and scale of observation. However these issues have yet to be addressed if we are to decide between a universal or a regional proxy for AMCs.

One can also ask if it is reasonable to use a sole measure of AMCs for a given catchment. Several authors (e.g., Cappus, 1960; Betson, 1964; Hewlett and Hibbert, 1967; Dunne and Black, 1970; Aryal et al., 2003; Ambroise, 2004) have shown that storm runoff usually originates from consistent parts of a catchment that often represent a small fraction of the whole topographic drainage area. This has been observed in a range of climatic regimes. Soil moisture is a critical hydrological state variable whose spatiotemporal variation indicates the presence of “active” or “contributing” areas or periods (Ambroise, 2004), and this relates to hydrologic connectivity. Dynamic connectivity of catchment source areas is controlled by the time-changing availability of surface/subsurface storm water, not only in terms of magnitude but also in terms frequency, duration, timing and rate (Bracken and Croke, 2007). Disconnected “active” areas involve water fluxes that do not contribute to the global output at a catchment outlet, while “contributing” areas to catchment response are composed of spatially connected “active” areas. Considering that both “active” and “contributing” areas are important in assessing a catchment initial state, do surrogate measures for AMCs reflect these dynamics? From a spatially-distributed point of view, the fact that all catchment areas are not “activated” at the same time may indicate that they are responsive to different hydro-meteorological factors. Similarly, the non-uniform contribution of source areas to streamflow may point towards different triggering hydro-meteorological factors. In that context, should multiple proxies for AMCs be used in order not to bias our understanding of a catchment hydrological behaviour?

This paper investigates that specific question. We examine the hydrological behaviour of a small headwater temperate humid forested system, the Hermine, for which several catchment-wide soil moisture patterns are available. The approach relies on point-scale temporal relations between actual soil moisture content values and selected meteorological-based indices so as to identify the surrogates for AMCs that are best suited to characterize the hydrological behaviour of the system. This simple exercise demonstrates that the sole reference to AMCs measures that are typically used in catchment hydrology would have prevented a full understanding of the Hermine catchment dynamics.

2 Methods

2.1 Hermine catchment

The Hermine is a 5.1 ha forested catchment located in the Lower Laurentians 80 km north of Montréal, Québec, Canada (Fig. 1a). The total annual precipitation to the region averages 1150 mm (±136 mm) over the last 30 years, of which 30% falls as snow (Biron et al., 1999). The catchment has a relief of 31 m and is drained by an ephemeral stream (Fig. 1b). Soils are 1 to 2 m deep Podzols developed over a bouldery glacial till. The presence of a confining layer at a depth of approximately 75 cm in the soil restricts root penetration, slows water infiltration and thus enhances the probability of rapid lateral shallow subsurface flow. In wet conditions, catchment-scale soil moisture patterns highly depend upon the asymmetric distribution of thick organic horizons; hydrophilic regions are preferentially located on the northern, steeper hillslopes. Near-surface soil moisture is also influenced by the catchment complex surface micro-topography due to fallen tree trunks and boulders at the soil surface. Other particular features of the Hermine include intermittent rills that are activated in very wet conditions (Fig. 1b) and a wet zone located in the upstream part of the valley bottom (Fig. 1b). Forest canopy is dominated by sugar maple and other deciduous tree species. Thus, transpiration is minimal between October and April so that changes in soil moisture and water table in that period are mostly governed by downslope drainage. The interception capacity of the forest canopy, combined with high summer potential evapotranspiration, greatly reduces the likelihood of high runoff except during heavy rainstorms or wet and cool periods. Forest canopy is, however, variable throughout the catchment, with a lower coverage density in upper parts of the southern slope near the catchment divide for example.

2.2 Topographic and soil moisture data

A surface digital elevation model (DEM) of the Hermine was obtained by interpolating 640 elevation points collected in the field. Elevation above the catchment outlet was then extracted for 121 sampling locations defined along a 15 by 15 m sampling grid in the catchment (Fig. 1c). The depth to the confining layer was measured at 257 points using a small hand auger that was forced vertically to refusal through the soil profile. For each sampling location, three auger to refusal measurements were made in a 1 m radius and checked for consistency to disregard data that are likely associated with the presence of individual clasts in the soil matrix instead of the targeted confining layer. Data were then interpolated into a subsurface DEM. In order to evaluate topographic influences on the spatial distribution of soil moisture, several secondary terrain attributes were derived from both the surface and the subsurface DEMs: local slope, contributing area and the topographic index (Beven and Kirkby, 1979) were computed using the $\mathbf{D}_\infty$ algorithm (Tarboton, 1997), while the multi-resolution valley bottom flatness (MRVBF) index was calculated after Gallant and Dowling (2003). The MRVBF index is derived from an elevation map and identifies flat and low regions at a range of scales. Its largest values flag the broadest and flattest low areas in the catchment. The depth to the confining layer was then extracted for each of the 121 sampling locations (Fig. 1d), together with the values of all secondary terrain attributes.

Soil moisture contents at multiple soil depths were surveyed using a portable 30-inch long rod equipped with a capacitance-based probe (AQUATERR Instruments & Automation) that was pushed into the ground to the desirable depth. On 16 occasions between August 2007 and July 2008, volumetric moisture content in the top 5, 15, 30 and 45 cm of the soil profile was measured on a 0 to 60% scale along the previously defined 15 by 15 m sampling grid, for a total of 121 sampling points. Figure 2 illustrates the contrast between surveys conducted at the Hermine, in terms of measured soil moisture patterns for different AMCs and discharges at the catchment outlet (Table 1).

2.3 Surrogates for AMCs and catchment response

For each of the 16 soil moisture survey dates, 12 temperature-based and precipitation-based indices (Table 1) were derived in order to assess their potential to serve as surrogates for antecedent conditions estimated from the soil moisture measurements. Mean daily potential evapotranspiration (PET) was computed after the temperature-based Hargreaves formula (Hargreaves, 1975). A first group of seven precipitation-based indices were used to capture the amount of rainfall added to the system over a given period x (AP_x) prior to the time of interest. AP_1, AP_2, AP_5, AP_7, AP_{10}, AP_{12} and AP_{14} were, respectively calculated as the cumulative rainfall over the 1, 2, 5, 7, 10, 12 and 14 days prior to the survey. A second group of precipitation-based indices were used to reflect the time distribution of the antecedent water inputs. DSP (i.e. days since precipitation) was computed as the number of days elapsed since the last recording at the rain gage, while the DSP_{10}, DSP_{20} and DSP_{30} indices were computed as the number of days elapsed since the last rainfall intensity exceeding 10, 20 and 30 mm d^{-1}, respectively. The ability of the survey mean soil moisture content (MSMC) to represent the catchment macrostate was also evaluated. Lastly, catchment discharges recorded on survey dates (current-day discharges, hereafter referred as CD_DISCH) were used to portray the integrated hydrological response at the catchment outlet.

2.4 Data analysis

Our methodology was twofold (Fig. 3). Firstly, we aimed to determine the nature and the strength of the relationships between point-scale soil moisture (i.e. soil moisture measured at each sampling point) and each of the AMCs and catchment response surrogates previously described. We hypothesized that the identified relationships would illustrate the variety of point-scale hydrologic behaviours that can be encountered within the Hermine catchment. Secondly, we examined the spatial organization of the nature and the strength of these point-scale relationships to link them with possible topographic controls.

For the determination of point-scale relationships, data cases were soil moisture survey dates ($n=16$), the independent variable was the chosen surrogate for AMCs and the dependent variable was the depth-specific, point-scale soil moisture content. No assumption was made on the form of the relationship between the dependent and the independent variables. Five regression models (i.e. linear, quadratic, cubic, semi-logarithmic and inverse), which represent five different types of possible relationships, were fitted to the data and compared so as to select the one with the best fit. These five models were only chosen for their simplicity. With the objectives of 1) assessing the potential of MSMC to represent the Hermine catchment macrostate, and 2) identifying catchment areas that might contribute to streamflow discharge, the statistical procedure was also applied to find the best regression model for both MSMC and CD_DISCH with point-scale soil moisture measurements. In each case, the selection of the best regression model was based on R-square values and significance levels ($p<0.05$). Throughout this paper, we refer to R-square as the proportion of variance in the dependent variable that is explained by the chosen regression model. It is defined as the ratio of the regression sum of squares (SSR) to the total sum of squares (SST), and it can be computed for any linear or nonlinear model given the knowledge of the total variance of the dependent variable (total sum of squares, SST), the proportion of variance due to the residuals (error sum of squares, SSE), and the proportion of variance due to the regression model (regression sum of squares, SSR=SST−SSE). The value of R-square often increases when a nonlinear model is used instead of a linear relationship. Some best-fit measures aside from R-square have been suggested in the literature to evaluate nonlinear models, namely the Akaike information criterion (AIC) or the Kullback-Leibler divergence (e.g., Cameron and Windmeijer, 1997; Kim and Cavanaugh, 2005). As our objective was to propose a simple methodological approach, we kept R-square as our only best-fit measure and we carefully examined its values so as not to opt for nonlinear relationships over linear ones unless the improvement in the proportion of explained variance was tangible.

The possible influence of catchment topography, both surface and subsurface, was studied with regards not only to the nature (e.g. linear versus quadratic, versus cubic, etc.) but also to the strength of the point-scale relationships between actual soil moisture and surrogate measures. Nonparametric Kruskal-Wallis tests were run to assess whether the different types of point-scale relationships were spatially associated with specific topographic properties. Spearman correlation coefficients were also computed between the strength of the point-scale relationships (i.e. *R*-square values) and the values of the terrain attributes.

3 Results

3.1 Point-scale relationships

Figures 4 and 5 illustrate the spatial heterogeneity in the Hermine when it comes to the relation between point-scale actual soil moisture measurements and any catchment-wide, meteorological-based proxy for AMCs. Figures 4 and 5 also show that the spatial patterns are highly dependent not only upon the chosen surrogate for AMCs but also upon the soil depth considered. For instance, only 20% of the soil moisture sampling sites at a 5 cm depth are significantly ($p<0.05$) associated with PET (Fig. 5). The best regression model for that relationship is a logarithmic one; however *R*-square values do not exceed 0.45. A similar result is obtained at a depth of 15 cm where only 16% of the sampling locations are related to PET, and that proportion drops to zero when depths of 30 or 45 cm are considered.

For precipitation-based indices computed from cumulative rainfall, especially AP_1, AP_2 and AP_5, linear relationships are mostly present at a 5 cm depth while nonlinear relationships tend to dominate from a depth of 15 cm and below (Fig. 4). At all depths, relationships between AP_1 and soil moisture content measurements are statistically significant ($p<0.05$) but generally weak; unlike relationships between AP_2 and soil moisture content that were mostly fitted with a cubic regression model ($0.25 \leq R$-square≤ 0.65) at depths of 15, 30 and 45 cm. With AP_5, linear, quadratic and cubic regression models are almost equally present at the 5 and 15 cm depths while only cubic and quadratic relationships dominate the patterns at depths of 30 and 45 cm. Significant relations between AP_5 and point-scale soil moisture content measurements are the strongest ($0.36 \leq R$-square≤ 0.74) and the most widespread over the Hermine catchment area. On the contrary, patterns associated with AP_7, AP_{10} and AP_{14} show very few, if any, significant relations. Relationships between AP_{12} and point-scale soil moisture content measurements are of interest not because of their magnitude but rather because they make up a spatial pattern that is a mirror image of the patterns associated with AP_1, AP_2 and AP_5 (Fig. 4). With AP_{12}, significant relationships are confined to a small area on the southern slope; that is opposed to their widespread presence on the northern hillslope and in the catchment upstream area when AP_1, AP_2 or AP_5 are used as surrogates for AMCs (Fig. 4).

Spatial patterns of point-scale relationships were also different depending upon the chosen rainfall intensity-based measure of AMCs. Figure 5 shows that for all soil depths, a large proportion of sampling locations are significantly, yet weakly related to DSP, yielding a patchwork of linear, cubic, quadratic and logarithmic negative relationships. When relations with DSP_{10} and DSP_{20} are evaluated, less heterogeneous patterns are observed with the predominance of negative logarithmic relationships for DSP_{10} and of positive inverse relationships for DSP_{20} (Fig. 5). Significant relationships between DSP_{30} and point-scale soil moisture content measurements are the most obvious at the 5 cm depth with a mix of strong linear, quadratic and cubic decreasing regression models.

For almost all sampling locations at all depths, significant relationships between soil moisture content measurements and MSMC are found ($0.25 \leq R$-square≤ 0.81, $p<0.05$). The vast majority of these relationships are quadratic, cubic or logarithmic (Fig. 5). The proportion of sampling locations sharing nonlinear relationships with MSMC is 44% at a depth of 5 cm and reaches 60% at a depth of 15 cm and even 80% at depths of 30 and 45 cm. As far as the variable CD_DISCH is concerned, the presence of statistically significant relations is highly dependent upon soil depth (Fig. 6). At

15 cm, only a few sampling locations are characterized by a cubic relationship between point-scale soil moisture content and CD_DISCH. At 30 and 45 cm, the spatial patterns of significant relationships include linear, quadratic, cubic and logarithmic regression models and resemble the spatial patterns obtained with AP_1, AP_2 and AP_5.

3.2 Topographic influences

Regardless of soil depth, no significant Spearman correlation coefficient was found between the strength (i.e. R-square) of the identified point-scale relationships and the values of any surface or subsurface terrain attribute. However, nonparametric Kruskal-Wallis tests showed that the nature of some relations (i.e. the presence of linear, quadratic, cubic, logarithmic or inverse relationships) was associated with topographic variables (Tables 2 and 3).

Elevation above the catchment outlet was the most consistent, statistically significant ($p<0.05$) control on the spatial patterns of relationships between AMCs proxy variables and soil moisture measurements. Figure 7 shows that at a depth of 5 cm, relationships between AP_1 and point-scale soil moisture content measurements are all polynomial (i.e. linear, quadratic or cubic), however the higher the elevation, the higher order of the relationship. Boxplots also show statistically significant differences in surface elevation depending on the nature of the relationship between point-scale soil moisture measurements and AP_5 at all depths (Fig. 7). As far as DSP_{20} is concerned, it is interesting to note that at a depth of 5 cm, no relationship with point-scale soil moisture measurements can be found at elevations below 20 m, yet statistically significant inverse regression models are fitted to the soil moisture and DSP_{20} data for sampling sites located above the 20 m elevation level (Fig. 7). At depths of 30 and 45 cm, all five types of relationships between point-scale soil moisture measurements and DSP_{20} are present, but mostly at elevations exceeding 10 m above the catchment outlet, with logarithmic relations being preferentially located in upper regions near the catchment divide. At the 5 cm depth, MSMC is linearly related to point-scale soil moisture content mainly for locations whose elevation is below 20 m, otherwise nonlinear relationships are observed. At depths of 30 and 45 cm, however, nonlinear relationships with MSMC expand across the whole range of elevation values (Fig. 7), thus making it difficult to discern any clear spatial pattern. As for the influence of surface elevation on the relationships between CD_DISCH and point-scale soil moisture measurements, it is only perceptible at depths of 5 and 15 cm (Fig. 7); however it should be remembered that relationships between CD_DISCH and point-scale soil moisture at these depths are very weak.

The second, most influential, topographic variable on the patterns of point-scale relationships between AMCs proxy variables and soil moisture was the MRVBF index of the surface and of the impermeable soil layer (Fig. 8). At a depth of 5 cm, we observe that the flatter the soil surface and the more irregular the soil-confining layer interface, the higher order the relationship between point-scale soil moisture measurements and AP_1. At that same depth of 5 cm, statistically significant inverse relationships were found between point-scale soil moisture content and DSP_{20} for locations with the most complex subsurface micro-topography (i.e. low values of the MRVBF index for the confining layer). The control exerted by terrain slope is perceptible at a depth of 30 cm (Table 2) as flat areas exhibit quadratic (negative) relationships with DSP_{30} while steeper areas rather exhibit cubic (negative) relationships with that same surrogate for AMCs. Soil moisture content at the sampling locations with the greatest contributing areas and hence the greatest values of the topographic index also showcase strong, negative, linear relationships with DSP_{30} at a depth of 30 cm (Fig. 8).

4 Discussion

The simple exercise conducted in this paper yielded new insight into the spatial representativity of proxy variables for AMCs or catchment response. While the relationships between actual soil moisture and several surrogate variables do exhibit strong spatial patterns (see examples in Figs. 4–6), some others show rather poor spatial organization, thus casting doubt on the use of a single surrogate to illustrate a catchment state of wetness. Reaching such a conclusion was only possible through the use of an exhaustive soil moisture dataset that covers nearly the entire set of hydrological conditions of the Hermine catchment (Table 1), except for the winter and early spring seasons. Even though the patterns illustrated in Figs. 4–6 only portray the spatial distribution of statistical relationships between actual soil moisture measurements and surrogate indices, they may reveal critical hydrological information. Hence, we argue that the simple statistical analyses conducted in this paper give lead to a better understanding of the spatial heterogeneity of hydrological patterns and processes in the Hermine catchment.

We hypothesized that maps of the point-scale relationships between soil moisture content measurements and surrogates for AMCs would provide information about variable "active" areas and their "activation" mechanisms. Indeed, locations for which soil moisture is strongly related with AMCs can be labelled as source areas. It is not surprising that the 16–20% of the near-surface catchment area subjected to the influence of PET are located on the upper parts of the southern slope, near the catchment divide and in a few other zones (Fig. 5) where canopy density is lower. A systematic assessment of canopy density needs to be done in the Hermine catchment in order to substantiate that hypothesis Much of the Hermine, especially near the catchment head and on the northern slope, seems to be "activated" by short-term AMCs as portrayed AP_1, AP_2 and AP_5 (Fig. 4). Statistically significant, even though weak, relations between soil moisture measurements and AP_{12} (Fig. 4) suggest that soil wetness is not persistent in the long-term except for a small portion of the catchment corresponding to a low-elevation wet zone and to thin soils developed over a bedrock outcrop. While 5 and 15 cm soil moisture usually shares linear relationships with AP_1, AP_2 and AP_5, nonlinear polynomial relationships (i.e. quadratic and cubic) are observed at depths of 30 and 45 cm (Fig. 4). This may be linked to the fact that the soil storage capacity is a function of the amount and timing of precipitation in addition to evapotranspiration (Ritcey and Wu, 1999), hence the nonlinear relationships.

We also hypothesized that the spatial patterns of point-scale relationships between soil moisture content and CD_DISCH is useful to identify catchment areas that might contribute to streamflow discharge. Locations for which soil moisture is strongly related with catchment discharge can be considered as contributing areas. Descriptions of the variable source area concept (e.g., Ambroise, 2004) have been built on the principle that catchment contributing areas are necessarily "active" areas, even though the opposite may not always be true. In that respect, it is worth noting that at depths of 30 and 45 cm, in particular, the spatial patterns of significant relationships between actual soil moisture measurements and CD_DISCH resemble the spatial patterns of significant relationships between actual soil moisture and AP_1, AP_2 and AP_5 (Figs. 4 and 6). Our approach makes it possible to distinguish near-surface from deeper potential "contributing" areas. At depths of 5 and 15 cm, locations are either not or nonlinearly related to CD_DISCH while at depths of 30 and 45 cm, a few sampling locations are involved in linear relationships with the overall catchment response (Fig. 6). From these results, we could argue that the particular locations of linear relationships hint towards sustained subsurface water fluxes leading to the catchment outlet. These locations could be associated with the absence of depressions to fill in the topography of the soil-confining layer interface; hence, they may be set in opposition to the other locations which may be subjected to a soil storage threshold to exceed before any lateral water fluxes can occur, hence the nonlinear relationships (Spence and Woo, 2003; Tromp-Van Meerveld and McDonnell, 2006b; Kusumastuti et al., 2007). Even though plausible, this hypothesis is not confirmed by the Kruskal-Wallis tests results in Tables 2 and 3. In fact, there are no statistically significant differences in subsurface terrain attributes between locations sharing linear relationships with CD_DISCH and locations sharing nonlinear relationships with CD_DISCH at depths of 30 and 45 cm. This conclusion highlights the main drawback of the purely statistical approach with regards to hypothesis testing, as the obtained regression models may not necessarily reflect causal relationships.

Concerning the results on MSMC, the important spatial extension of statistically significant relations with point-scale soil moisture content at all four depths indicates that it is a good surrogate for describing the catchment soil moisture macrostate. This is in accordance with the methodology of several previous studies (e.g., Thierfelder et al., 2003; Grant et al., 2004; James and Roulet, 2009) that relied on the use of the catchment mean shallow soil wetness for process understanding or modeling purposes. We, however, found that the less shallow the soil depth considered, the more locations whose soil moisture measurements were nonlinearly related to MSMC (Fig. 5). Furthermore, even at the 5 cm depth, relations between point-scale soil moisture measurements and MSMC were linear mainly for sampling sites located less than 20 m above the catchment outlet. This result requires further investigation as to how representative the MSMC really is with changing depths and as we move near the Hermine catchment divide.

It must be stressed that the sole reliance on indices often used in catchment hydrology, namely AP_7 and AP_{10}, would have led us to rely on a surrogate measure that is not related to soil moisture measurements in the Hermine. Even though soil moisture proxies based on antecedent rainfall can give good results (e.g., Kohler and Lindsey, 1951; Longobardi et al., 2003), the choice of the antecedent temporal window is crucial. In our case, AP_5 is the best index to use as a surrogate for AMCs in the Hermine catchment while AP_1, AP_2 and AP_{12} yield fairly good results. Kohler and Lindsey (1951) have argued that indices simply computed from the number of days since the last rain are “obviously insensitive and should not be used if accurate results are required” (p. 2). This statement does not reflect the results obtained for the Hermine catchment, especially when not only the days since the last rain but also the rainfall intensity are considered. Statistically significant relationships were obtained between point-scale soil moisture measurements and DSP, DSP_{10}, DSP_{20} and DSP_{30}. For DSP_{20}, a significant topographic control was even identified at the 5 cm depth, as inverse relationships with soil moisture were found for sampling sites located at least 20 m above the catchment outlet while barely any significant relations were obtained below that elevation (Fig. 7). It is also worth mentioning that previous-day discharges were also used as surrogates for AMCs (data not shown) but they were not involved in any significant relationship with point-scale soil moisture measurements; this result is contradictory to the affirmation of Kohler and Lindsey (1951) who argued that baseflow-derived indices provided reasonably good results in humid and sub-humid regions.

It is interesting to compare results obtained from previous studies in the Hermine catchment with the conclusions of the current paper. For instance, the same soil moisture content dataset was analyzed to identify dominant organizing scales of soil moisture and their topographic controls (Ali et al., 2010). The importance of DSP_{30}, in particular, was then revealed: at a depth of 15 cm, the catchment areas subjected to the influence of DSP_{30} were present at the broad (>1.4 ha) and the very large (0.85–1.4 ha) characteristic scales whereas at a depth of 45 cm, DSP_{30} only influenced soil moisture at scales below 0.85 ha. These conclusions are consistent with the dynamics illustrated in Fig. 5. Furthermore, previous results corroborate the fact that relations between actual soil moisture and AP_7 or AP_{14} are very rare and can only be perceived at very fine characteristic scales (<0.1 ha). This comparison sheds light on the scale-dependent spatial representativity of AMCs surrogate measures. Ali et al. (2010), however, did not identify any significant relations between soil moisture and AP_2 at any characteristic scales, while it only captured the influence of AP_5 at the 0.54–0.85 ha scale and the influence of AP_{12} at the 0.02–0.1 ha scale. These results are opposite with some of the dynamics illustrated in Fig. 4.

In a paper aiming to identify hydrologically representative connectivity metrics in the Hermine catchment, Ali and Roy (2010) found that the spatial connectedness of locations whose volumetric soil moisture content exceeded 30% was dependent upon AP_7. The relationship between connectivity and AP_7 then had the form of a step function, which may explain why it was not captured by any of the tested regression models in the current paper. Geochemical data were also used to assess the temporal variability in the nature of catchment sources and their contributions to streamflow (Ali et al., 2001). Multiyear daily stream chemistry data were broken down into several hydrologic scenarios to reflect different conditions with respect to stream discharge and two surrogates for antecedent catchment wetness (i.e. AP_2 and AP_7). From an end-member mixing analysis (EMMA) applied to each sub-dataset associated with each hydrologic scenario, it was found that the nature of the identified end-members did not vary significantly among the tested scenarios. However, their relative contributions to streamflow were dependent upon AP_2 rather than AP_7; thus echoing the conclusions of the present study about the appropriateness of AP_2 as a proxy for the Hermine catchment AMCs and the insignificance of AP_7 in that regard. Lastly, a combination of multivariate statistical methods was used to identify dominant rainfall-runoff behaviours in the Hermine catchment (Ali et al., 2010). On the contrary to the current paper, it was then found that AP_{10} had an influence on the catchment behaviour only when the cumulative antecedent rainfall amounts lay in the range of 24.5 to 40.5 mm. There again, such a relationship between catchment discharge and AP_{10} can be schematized as a rectangular function that does not bear any resemblance with any of the regression models tested in this paper. This analysis shows some inconsistencies in identifying the appropriate AMCs surrogate measure. It highlights the sensitivity of the results to the nature of the relations and of the ensuing regression model that is used.

Our results are catchment specific. They pertain to a small forested watershed with relatively steep slopes in a temperate humid climate. The small scale of the headwater basin and its relief may play a role on the optimal antecedent temporal window size that has been identified (i.e. 5 days) through the analysis. The approach, however, has a general value as the simple analysis described in this paper can be repeated for several catchments under various climatic regimes and for which spatially-detailed soil moisture data are available. This will allow the hydrological community to compare findings and maybe derive guidelines regarding the choice of proxy measures of AMCs in catchments with specific climatic and topographic characteristics.

5 Conclusions

This paper aimed at determining whether or not multiple surrogates for AMCs had to be used in order to understand the hydrological behaviour of a catchment. With regards to the Hermine catchment, the answer to that question is affirmative. Without making any assumption on active processes, we computed the point-scale temporal relations between actual soil moisture measurements and commonly used meteorological-based indices so as to identify the surrogates for AMCs that are best suited to the Hermine catchment. Two principal results stood out. Firstly, it was shown that the sole reference to AMCs indices often used in catchment hydrology (i.e. AP_7 or AP_{10}) does not provide a complete understanding of the Hermine catchment dynamics; soil moisture was not related to cumulative rainfall amounts over antecedent temporal windows of seven or ten days. Secondly, the relationships between point-scale soil moisture measurements and surrogates for AMCs were not spatially homogeneous, thus revealing a mosaic of linear and nonlinear catchment "active" and "contributing" sources whose location was sometimes controlled by surface terrain attributes or the topography of the soil-confining layer interface. These results represent a step forward in developing a hydrological conceptual model for the Hermine catchment as they indicate depth-specific processes and spatially-variable triggering conditions. Such hydrological behaviour may also exist in other catchments. The analysis also raises several questions on the use of surrogate AMCs measures and on the generalization of results obtained with a single surrogate. Further investigations are, however, necessary to establish robust, causal relationships between soil moisture and meteorological-based proxies for AMCs and then derive guidelines concerning the best surrogate choice.

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Table 1. Surrogates for AMCs, catchment macrostate and hydrologic response for 16 soil moisture surveys in the Hermine. See meaning of abbreviations in text.

Date of survey	AP$_1$ (mm)	AP$_2$ (mm)	AP$_5$ (mm)	AP$_7$ (mm)	AP$_{10}$ (mm)	AP$_{12}$ (mm)	AP$_{14}$ (mm)
6 Aug 2007	0	0	4	4	36	36	36
13 Aug 2007	12	12	17	44	44	48	48
7 Sep 2007	8	8	8	8	8	22	44
14 Sep 2007	0	0	14	14	15	22	22
21 Sep 2007	0	0	0	18	22	32	32
28 Sep 2007	4	4	4	4	4	4	22
5 Oct 2007	0	0	0	6	10	10	10
12 Oct 2007	25	25	40	42	42	42	48
26 Oct 2007	0	0	15	43	43	43	67
2 Nov 2007	3	3	3	33	36	48	76
9 Nov 2007	0	0	17	17	20	20	50
20 May 2008	10	20	36	39	39	39	54
2 Jun 2008	2	21	27	29	29	49	61
17 Jun 2008	13	14	14	29	29	37	37
15 Jul 2008	2	3	19	43	43	54	59
21 Jul 2008	0	0	33	35	42	73	75

Date of survey	DSP (d)	DSP$_{10}$ (d)	DSP$_{20}$ (d)	DSP$_{30}$ (d)	PET (mm/d)	MSMC (% vol)	CD_DISCH (mm/d)
6 Aug 2007	0	0	0	9	2.61	33.8	0.66
13 Aug 2007	0	1	7	16	2.58	23.3	0.22
7 Sep 2007	1	9	15	41	3.15	27.0	0.05
14 Sep 2007	0	3	22	48	2.19	29.0	0.07
21 Sep 2007	6	6	29	55	2.07	27.7	0.06
28 Sep 2007	0	13	36	62	1.73	27.9	0.10
5 Oct 2007	7	20	43	69	2.40	17.3	0.09
12 Oct 2007	0	0	1	76	1.49	39.6	5.87
26 Oct 2007	3	3	7	90	1.33	23.1	0.91
2 Nov 2007	1	6	6	6	1.23	21.5	1.52
9 Nov 2007	3	3	13	13	0.86	21.1	1.71
20 May 2008	0	2	22	141	1.87	34.4	1.80
2 Jun 2008	0	2	35	154	2.89	30.0	0.83
17 Jun 2008	0	1	50	169	2.37	32.2	0.52
15 Jul 2008	1	3	6	197	2.51	31.5	0.42
21 Jul 2008	0	0	3	203	2.44	35.2	0.78

Table 2. Influence of catchment surface topography (rows) on the nature of the point-scale relationships between soil moisture content and various surrogates (columns). Reported p-values are significant and suggest that at least one relationship type is associated with a median value of the studied topographic variable that is significantly different from the others.

	PET	AP_1	AP_2	AP_5	AP_7	AP_{10}	AP_{12}	AP_{14}	DSP (d)	DSP_{10}	DSP_{20}	DSP_{30}	MSMC	CD_DISCH
5 cm														
Elevation		0.0162	0.0002	0.0009		0.0263					0.0000	0.0296	0.0002	0.0016
Slope							0.0469							
Cont. area														
Topo. index														
MRVBF														
15 cm														
Elevation		0.0463	0.0023	0.0002							0.0097	0.0010	0.0275	
Slope	0.0450													
Cont. area										0.0367				0.0263
Topo. index											0.0191			0.0280
MRVBF											0.0235			
30 cm														
Elevation			0.0000	0.0010		0.0152	0.0030	0.0006		0.0000				
Slope												0.0019		
Cont. area														
Topo. index												0.0456		
MRVBF														
45 cm														
Elevation			0.0038	0.0054						0.0428		0.0334	0.0367	
Slope			0.0142							0.0043				
Cont. area		0.0407												
Topo. index			0.0106						0.0122					
MRVBF			0.0201										0.0170	

Cont. area: contributing area
Topo. index: topographic index
MRVBF: multi-resolution valley bottom flatness index

Table 3. Influence of the soil confining layer topography (rows) on the nature of the point-scale relationships between soil moisture content and various surrogates (columns). Reported p-values are significant and suggest that at least one relationship type is associated with a median value of the studied topographic variable that is significantly different from the others.

	PET	AP_1	AP_2	AP_5	AP_7	AP_{10}	AP_{12}	AP_{14}	DSP (d)	DSP_{10}	DSP_{20}	DSP_{30}	MSMC	CD_DISCH
5 cm														
Depth to layer				0.0000								0.0077		
Slope						0.0132								
Cont. area	0.0238													
Topo. index											0.0094			
MRVBF		0.0489									0.0036			
15 cm														
Depth to layer														
Slope														
Cont. area				0.0291										
Topo. index	0.0362										0.0469			
MRVBF													0.0467	
30 cm														
Depth to layer							0.0000	0.0000						
Slope														
Cont. area										0.0090				
Topo. index							0.0251			0.0321				
MRVBF														
45 cm														
Depth to layer														
Slope						0.0152					0.0328			
Cont. area														
Topo. index										0.0040				
MRVBF														

Cont. area: contributing area
Topo. index: topographic index
MRVBF: multi-resolution valley bottom flatness index

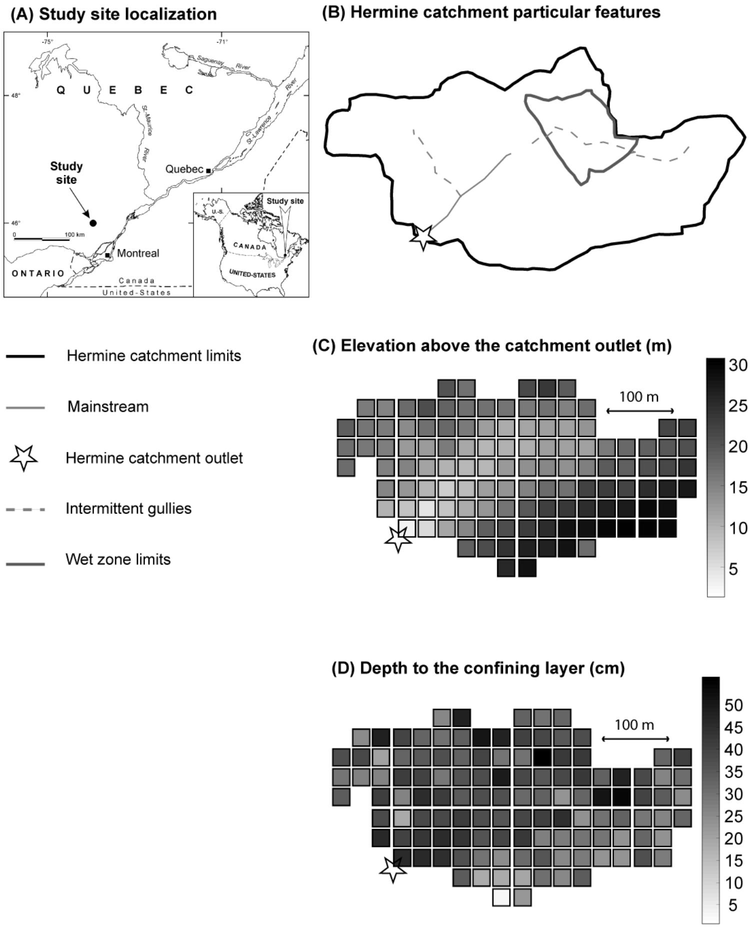


Fig. 1. (A) Location of the Hermine catchment; **(B)** Hermine catchment particular features; **(C)** Elevation above the catchment outlet; and **(D)** Depth to the confining layer for each of the 121 soil moisture sampling locations.

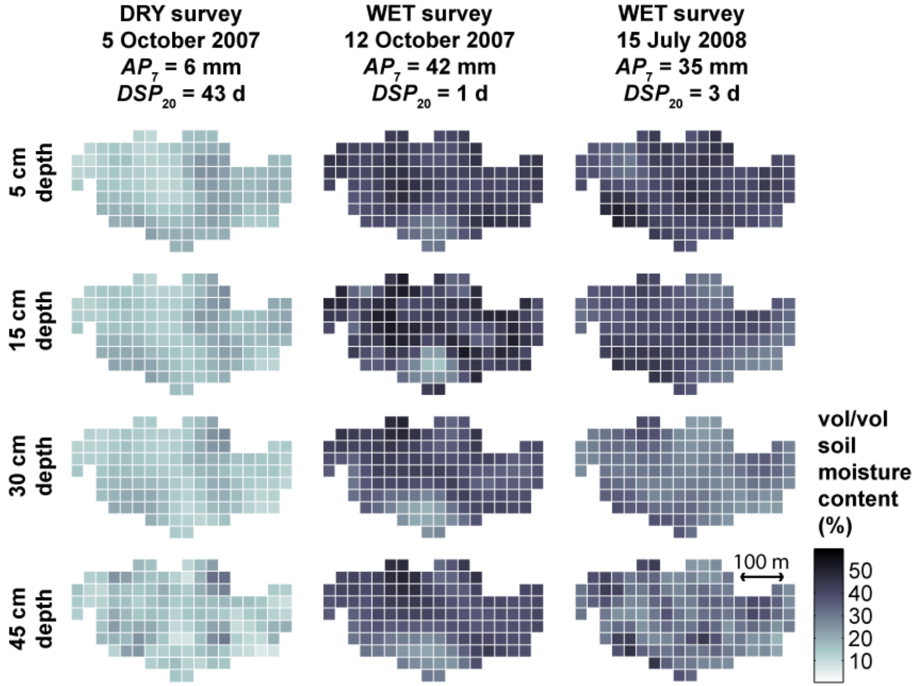
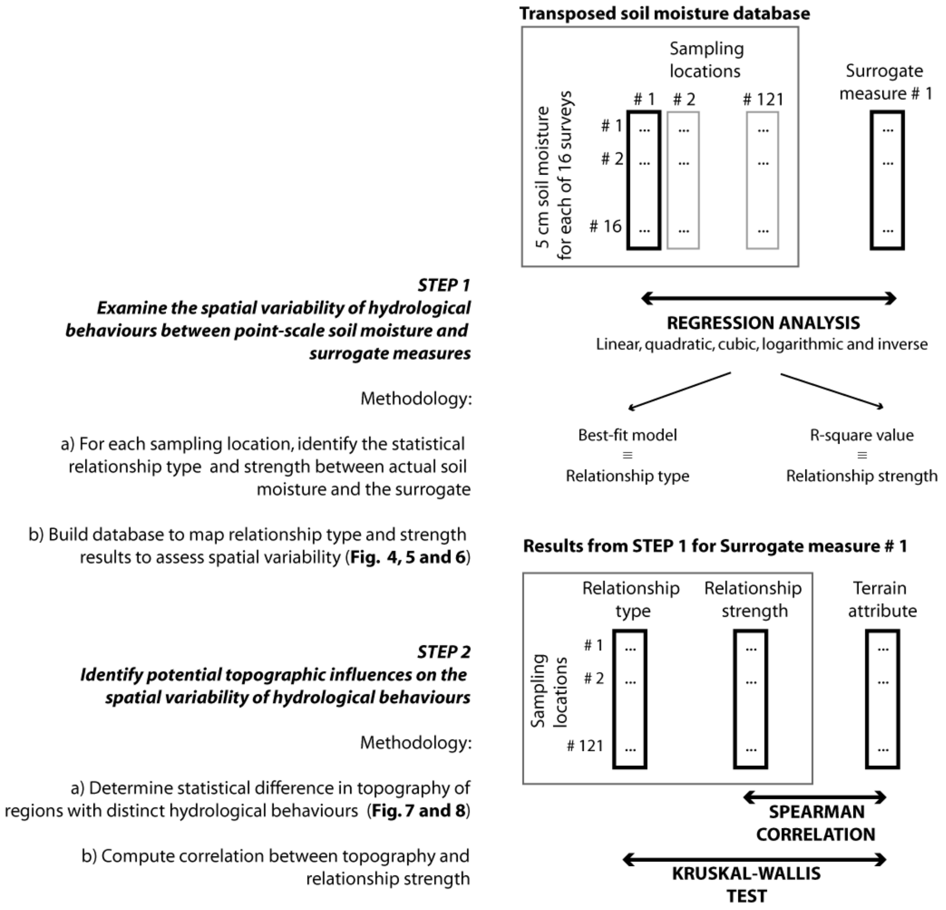


Fig. 2. Sample soil moisture maps obtained after three contrasted surveys in the Hermine catchment.



STEP 1

Examine the spatial variability of hydrological behaviours between point-scale soil moisture and surrogate measures

Methodology:

a) For each sampling location, identify the statistical relationship type and strength between actual soil moisture and the surrogate

b) Build database to map relationship type and strength results to assess spatial variability (**Fig. 4, 5 and 6**)

STEP 2

Identify potential topographic influences on the spatial variability of hydrological behaviours

Methodology:

a) Determine statistical difference in topography of regions with distinct hydrological behaviours (**Fig. 7 and 8**)

b) Compute correlation between topography and relationship strength

Fig. 3. Methodological approach used in this paper.

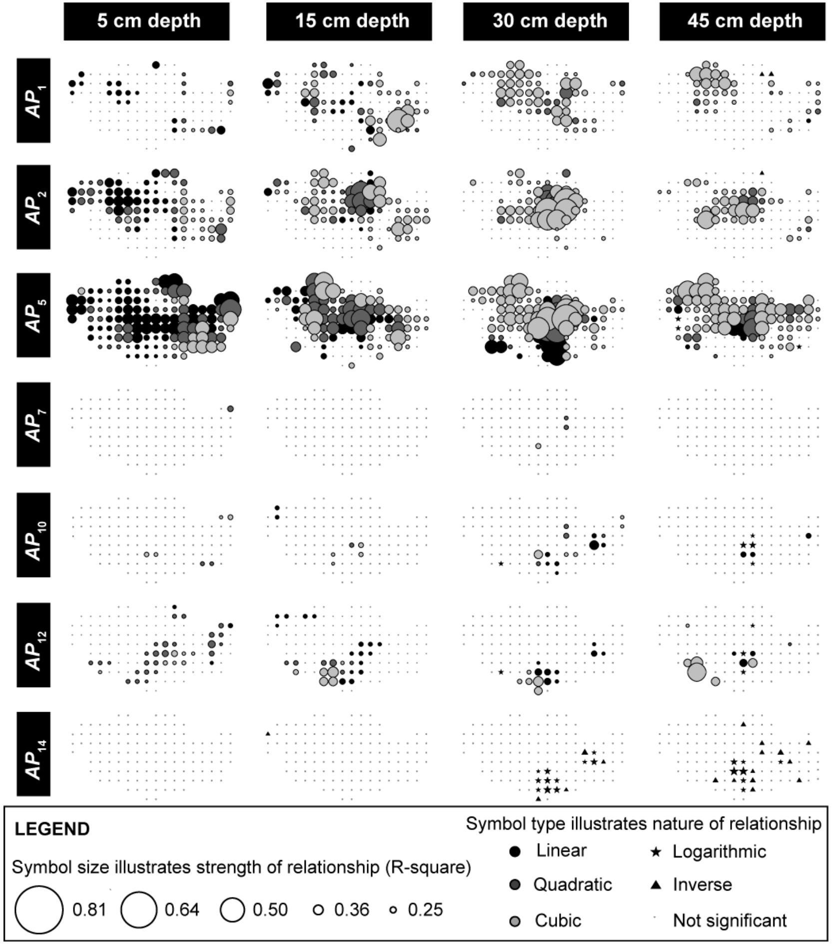


Fig. 4. Nature and strength of the relationships between point-scale soil moisture content and AP_x indices (x=1, 2, 5, 7, 10, 12 or 14 days) used as surrogates for AMCs.

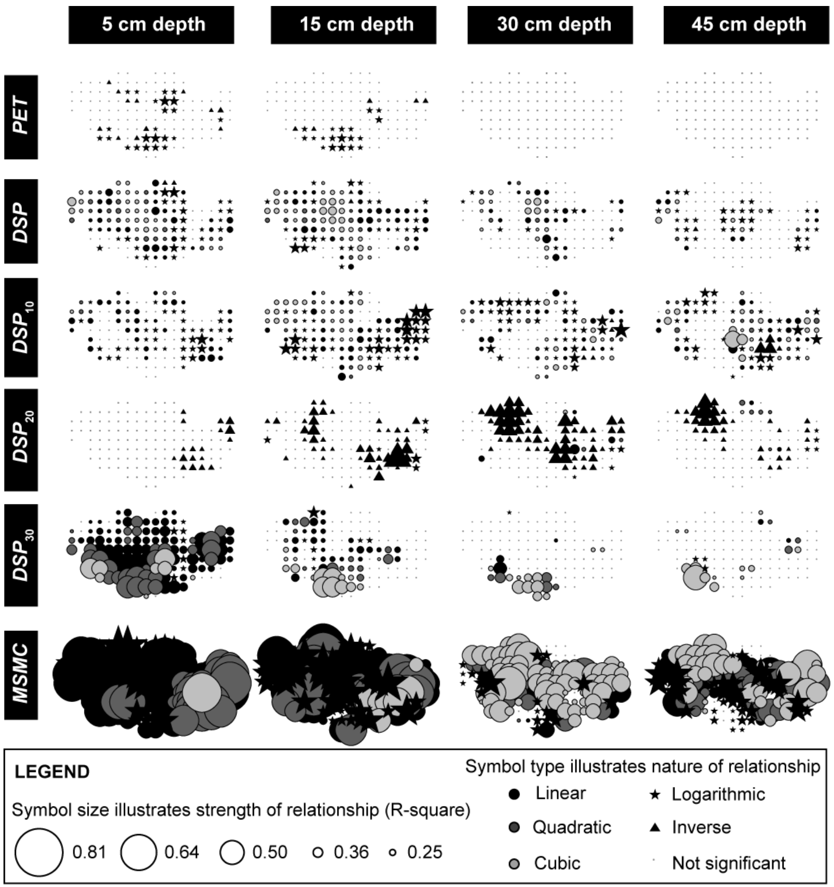


Fig. 5. Nature and strength of the relationships between point-scale soil moisture content, PET and SINCE$_x$ indices (x=0, 10, 20 or 30 mm/d) used as surrogates for AMCs, and MSMC used as a surrogate for the Hermine catchment macro-state.

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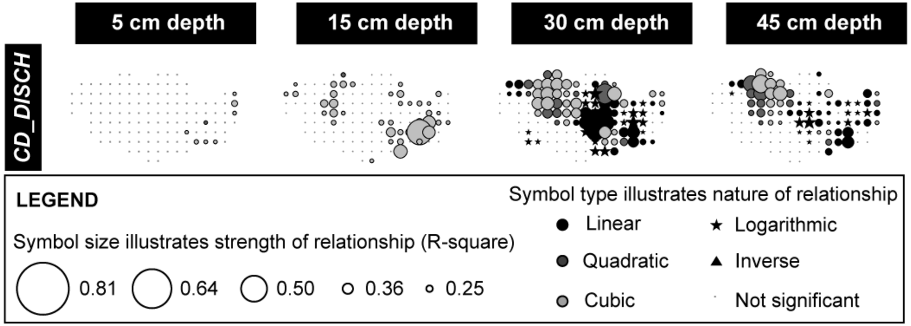

Fig. 6. Nature and strength of the relationships between point-scale soil moisture content and CD_DISCH used as a surrogate for the Hermine catchment response.

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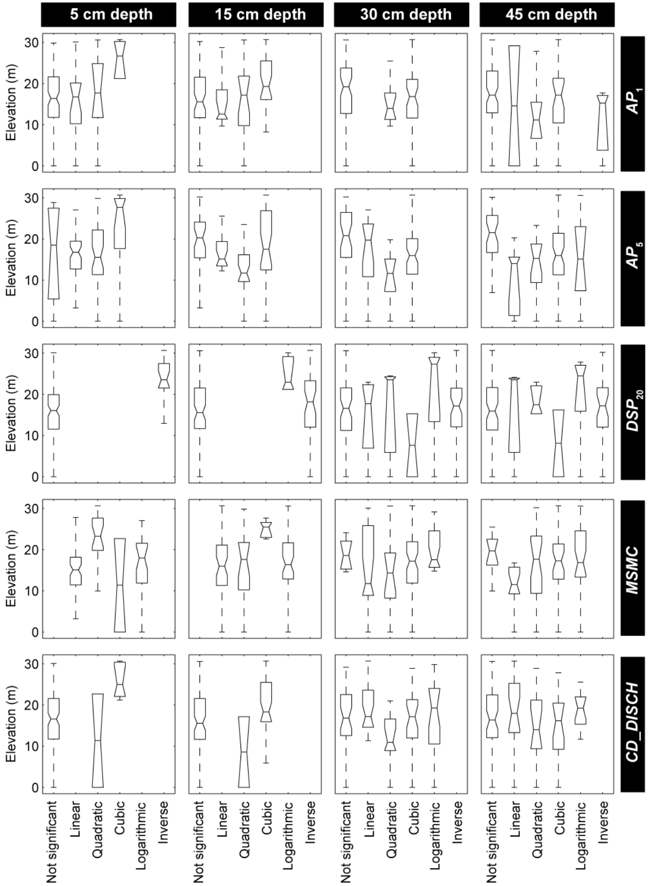

Fig. 7. Influence of surface topography (elevation above the catchment outlet) on the nature of the relationship between point-scale soil moisture (columns) and selected proxies for AMCs, catchment macrostate and catchment response (rows) in the Hermine.

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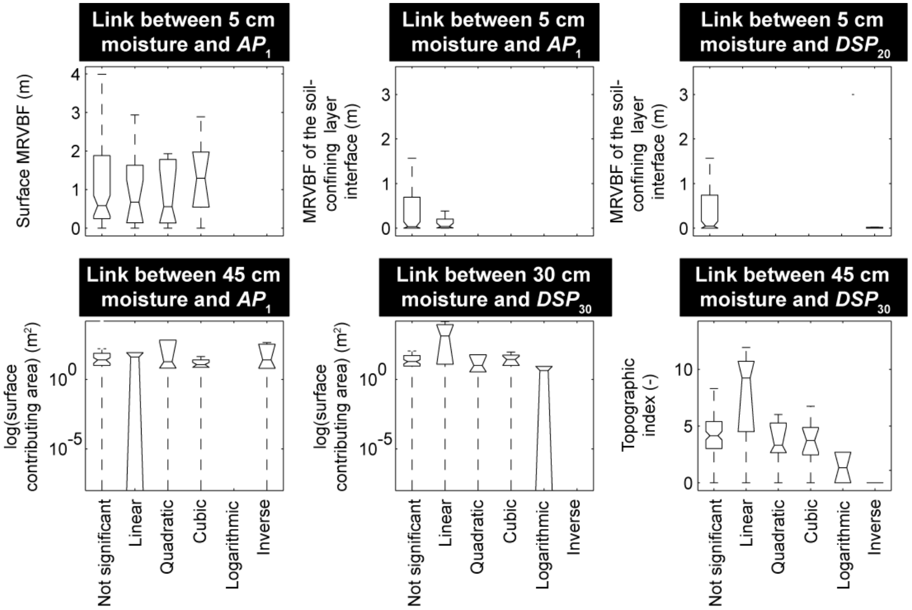

Fig. 8. Influence of various topographic properties on the nature of the relationship between point-scale soil moisture and selected surrogate measures for AMCs.