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# McMaster Mesonet soil moisture dataset: description and spatio-temporal variability analysis

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## Abstract

This paper introduces and describes the hourly high resolution soil moisture dataset continuously recorded by the McMaster Mesonet located in the Hamilton-Halton Watershed in Southern Ontario, Canada. The McMaster Mesonet consists of a network of time domain reflectometer (TDR) probes collecting hourly soil moisture data at six depths between 10 cm and 100 cm at nine locations per site spread across four sites in the 1250 km$^2$ watershed. The sites for the soil moisture arrays are designed to further improve understanding of soil moisture dynamics in a cold and snowy climate and to capture soil moisture transitions in areas that have different topography, soil and landcover. The McMaster Mesonet soil moisture constitutes a unique database in Canada because of its high spatio-temporal resolution. In order to provide some insight into the dominant processes at the McMaster Mesonet sites a spatio-temporal and temporal stability analysis were conducted to identify spatio-temporal patterns in the data and to suggest some physical interpretation of soil moisture variability. It was found that the seasonal Canadian climate causes a transition in soil moisture patterns at seasonal time scales. During winter and early spring months, and at the meadow sites, soil moisture distribution is governed by topographic redistribution, whereas following efflorescence in the spring and summer, soil moisture spatial distribution at the forested site was equally dominated by vegetation canopy. Analysis of short-term temporal stability revealed that the relative difference between sites was maintained unless there was significant rainfall (> 20 mm) or wet conditions a priori. Following a disturbance in the spatial soil moisture distribution due to wetting, the relative soil moisture pattern re-emerged in 18 to 24 h. Access to the McMaster Mesonet data can be provided by visiting www.hydrology.mcmaster.ca.

## 1 Introduction

The spatial and temporal variability of soil moisture both at the surface and in the root-zone is an important control in many hydrological and atmospheric fluxes. These fluxes play a critical role in water and energy balances, and have both a direct and indirect impact on water resources and local climate. Soil moisture is of great significance for scientific and operational applications such as flood prediction and forecasting (Komma et al., 2008; Mahanama et al., 2008; Brocca et al., 2009), numerical weather prediction (Mohr et al., 2003; Loew et al., 2009; Alavi et al., 2010), climate modeling (Merlin et al., 2006; Seneviratne et al., 2010) and other disciplines, because it controls the partition between infiltration and runoff as well as latent and sensible heat fluxes. The potential of soil moisture data in these areas and others is being realized through recent technological advances, which have allowed for detailed in situ and remote soil moisture monitoring. As monitoring programs become more widespread and temporally consistent, they are providing a better understanding of the processes which determine the spatial and temporal distribution of soil moisture. The spatial distribution of soil moisture is determined by an organized structure that is perturbed by stochastic forcing (Bronstert and Bardossy, 1999), and analyses of soil moisture monitoring programs have revealed that the relative dominance of any organized or stochastic factor varies with basin, soil, topography, vegetation, meteorological and scale characteristics. However, no continuous high resolution soil moisture data was available in Canada to carry out such analyses. The McMaster Mesonet was establised to fill that gap.

With respect to spatial soil moisture distribution, some studies have found that soil moisture variability increases in wet conditions (Famiglietti et al., 1998; Vivoni et al., 2008), while others have found variability increases in dry conditions (Jacobs et al., 2004; Bosch et al., 2006; Choi and Jacobs, 2007; Brocca et al., 2010). Analyzing the results from many studies Brocca et al. (2007) found that in humid climates, spatial variability is greater when conditions are dry, whereas semi-arid environments have the highest variability in wet conditions. These relationships are also subject to considerations of scale and topography. For example, scale is important as homogenous rainfall tends to decrease soil moisture variability and heterogeneous rainfall increases it (Cosh et al., 2004), whereas Famiglietti et al. (1998) found that following a rainstorm upper portions of a hillslope were more variable than lower portions of the hillslope causing an overall increase in variability when the entire landscape was considered. At smaller scales, precipitation is generally homogenous and the redistribution of soil moisture by topography, soil texture and vegetation become important post precipitation (Wilson et al., 2003; Famiglietti et al., 2008). During wetting, soil moisture variability is dominated by the soils infiltration capacity and topographic redistribution (Famiglietti et al., 1998; Western and Bloschl, 1999; Western et al., 2004; Vivoni et al., 2008; Heathman et al., 2009) while, under dry conditions variability is maintained by the soil water holding capacity and concavity of the surface (Famiglietti et al., 1998; Peters-Lidard et al., 2001; Vivoni et al., 2008). Vegetation is also a potentially important predictor of soil moisture distribution which can redistribute soil moisture affording a homogenizing effect (Ivanov et al., 2010) or partially explain soil moisture spatial variability in some landscapes (Hupet and Vanclooster, 2002; Bosch et al., 2006), whereas in others that the role of vegetation in soil moisture distribution is only minor (Cosh et al., 2004). Vachaud et al. (1985) noticed that the relative rank of soil moisture at a particular location with respect to similar nearby locations was persistent in time, leading to the assertion of temporal stability, or more appropriately rank stability (Chen, 2006). The presence of temporally stable soil moisture patterns has been noted during several soil moisture campaigns (Martinez-Fernandez and Ceballos 2003; Cosh et al., 2004; Bosch et al., 2006; Vivoni et al., 2008) and has also been found to result from soil, topographic and vegetation influences (Vivoni et al., 2008). However, flat topography and soil moisture redistribution have also been observed to result in poor temporal stability (Mohanty et al., 2000b; Mohanty and Skaggs, 2001). None of those soil moisture dynamics analysis studies was conducted in Canada because of the lack of appropriate soil moisture data. The role of seasonal effects on soil moisture variability and stability in cold and snowy climates remains an open research area. The McMaster Mesonet database will help to fill that gap as well.

Over the past decade several soil moisture monitoring efforts have been undertaken to characterize the spatial-temporal distribution of soil moisture either through intensive short term monitoring efforts for large areas such as the Southern Great Plains (SGP) (Familglietti et al., 1997; Mohanty et al., 2000b; Ryu and Famiglietti, 2005, 2006) and Soil Moisture Experiments (SMEX) series (Cosh et al., 2004; Bosch et al., 2006; Choi and Jacobs, 2007; Das et al., 2008) or long-term monitoring of catchment scale soil moisture and for calibration/validation of radiometer scale (∼ 40 km) soil moisture products (Ceballos et al., 2005; Albergel et al., 2008; Lebel et al., 2009; Brocca et al., 2010). While coarse resolution soil moisture is relatively abundant and has been shown to enhance hydrological and atmospheric modelling, the advantage of high resolution datasets is increasingly recognized (Wood et al., 2011) and the influence of small scale heterogeneity has been demonstrated (Merlin et al., 2006; Alavi et al., 2010; Minet et al., 2010). Most efforts to characterize soil moisture data at high spatial resolution are either of a limited lifespan (Famiglietti et al., 1998; Mohanty et al., 2000a; Hupet and Vanclooster, 2002) or are sampled periodically (Martinez-Fernandez and Ceballos, 2003; Wilson et al., 2003; Western et al., 2004). What has been missing to date is a long-term soil moisture experiment at high spatio-temporal resolution in order to understand and to quantify soil moisture variability and processes, specially at higher latitudes. The McMaster Mesonet was designed to provide appropriate soil moisture information needed for process undertanding and modeling, and developing soil moisture retrieval and extension algorithms.

This paper introduces and describes the long-term high resolution McMaster Mesonet dataset located in the 1250 km$^2$ Hamilton-Halton Watershed in Southern Ontario, Canada. It also provides a spatio-temporal analysis of the hourly soil moisture data collected at four sites since autumn 2006. The experiment was designed specifically for application to high resolution remote sensing soil moisture validation, hydrological data assimilation, and process understanding. The unique aspect of this dataset is the multiple soil moisture profiles that are collected at each site allowing for the characterization of field scale soil moisture variability which will provide insite into the influence of topography, vegetation and atmospheric conditions on small scale soil moisture dynamics. Also, most soil moisture experiments described in the literature are from the USA, Europe and Australia and so, to the best knowledge of the authors, this paper represents the first attempt to describe long term soil moisture dynamics in Canada. The main dataset consists of a series of four high resolution soil moisture arrays collecting hourly distributed soil moisture profile information since 2006 with an expected lifespan of fifteen years. The soil moisture data is supplemented by six weather stations and nine rain gauges distributed throughout the watershed. This dataset can be made available to the broader research community by visiting the website www.hydrology.mcmaster.ca and plans are underway to include the dataset in the International Soil Moisture Network (Dorigo et al., 2011). This paper would serve as an essential reference for the McMaster Mesonet data users. The paper is broken down into the following sections. Section 2 will provide an overview of the Hamilton-Halton Watershed and the McMaster Mesonet dataset. Section 3 will outline methods used in this paper and Sect. 4 will present a summary of the Mesonet data and the spatio-temporal analysis results. Section 5 will provide concluding remarks and will comment on the implications and benefits of high spatio-temporal resolution soil moisture data.

## 2 McMaster Mesonet

### 2.1 Hamilton-Halton Watershed

The Hamilton-Halton Watershed (Fig. 1) is part of the Lake Ontario drainage basin in Ontario, Canada and has approximately 980 km$^2$ rural agricultural/forested land and 270 km$^2$ of urbanized/industrial land. The urbanized land in the watershed is concentrated within a band that extends approximately 7.5 km from the Lake Ontario shoreline, with the notable exception of the Town of Milton which covers an area of 25 km$^2$, in the northern-central part of the watershed. The major geographic features include the Lake Iroquois Plains, which are an ancient glacial extension of the current Lake Ontario shoreline and the Niagara Escarpment. The area surrounding the Niagara Escarpment is primarily mixed deciduous/coniferous woodland, and agriculture dominates the remainder of the rural area. The primary crops are maize, soy and grains with some tender fruit crops. The watershed is sub-divided into six primary sub-watersheds, Sixteen Mile Creek, Bronte Creek, North Shore, Grindstone Creek, Spencer Creek and Red Hill Creek, each with their own network of tributaries. Sixteen Mile Creek is the northernmost sub-watershed and covers an area of 357 km$^2$ and is predominantly agricultural. The Bronte Creek Watershed encompasses an area of 304 km$^2$ and has the largest proportion of forested area around the Niagara Escarpment. Grindstone Creek has a catchment area of 99 km$^2$ and is largely rural agricultural with forest and some urban area in the south east. Both North Shore Creek (44 km$^2$) and Red Hill Creek (93 km$^2$) are predominantly urban areas and have been modified to accommodate urban storm water management. Spencer Creek encompasses an area of 260 km$^2$ and is predominantly rural/agricultural and includes part of the City of Hamilton and forested area around the Niagara Escarpment in the south eastern portion of the sub-watershed. It is important to note that areas reported herein are consistent with what is portrayed in Fig. 1, however, in reality the sub-watersheds as reported also contain small waterways which drain directly into Lake Ontario but are not distinguished herein.

The climate of the watershed can be classified as humid continental with average annual precipitation of 910 mm distributed evenly throughout the year. The watershed experiences four distinct seasons, with average summer temperatures of 21 °C and average winter temperatures of −6 °C (1971 to 2000 Canadian Climate Normals). A time series plot of climate variables and average soil moisture data from the McMaster Mesonet for 2006 to 2012 can be seen in Fig. 2 and a climate summary can be found in Table 2. The monthly and annual climate patterns at the Brittania weather station, located in the centre of the watershed, and the long term climate normals for the Hamilton Airport (5 km south of watershed) are presented for comparison. It should be noted that the Mesonet precipitation presented in Table 2 represents primarily rainfall as there is no active collection of data for snow water equivalent. The climate in the watershed is similar to the climate normals, with the exception of 2007, which had considerably lower than normal summer precipitation. Consequently, a prolonged period of low soil moisture can be seen throughout the summer of 2007 in Figs. 2 and 6 which is nearly two standard deviations below the mean soil moisture for the study period. A similar dry spell occured during the summer of 2011, but was compensated for annually by a wetter than normal spring and autumn in that same year. The climatic variability in the watershed during the course of study is ideal for studying soil moisture variability as a large variety of conditions have been observed within a relatively short period of study, by climatological standards.

## 2.2 Data description

For the sake of clarity, we will discuss the terminology which is used throughout this article. A soil moisture "site" refers to the location of an entire soil moisture array, i.e. Kelso 1 (K1), Kelso 2 (K2), Governor Road (GR) or Orchard (OR). Each site contains nine stations which are numbered from 1 to 9, where a "station" refers to a vertical soil moisture profile at a particular geographic location (Figs. 3 and 4). A station has six associated measurements for each sampling period for the six depths indicated in Table 2. Soil moisture characterized as "daily" refers to the mean value, and its variance, of a discrete 24 h period measured using Eastern Standard Time.

The McMaster Mesonet provides long term hourly soil moisture data at four sites, Kelso 1, Kelso 2, Governor Road and Orchard which have been collecting data continuously since 2006. Each site contains 54 Campbell Scientific CS616 multiplexed time domain reflectometery (TDR) probes attached to a CR10X datalogger through nine soil moisture profile stations with six TDR probes each. Each profile station performs measurement at six depths between 10 to 100 cm, with specific depths given in Table 2. At each of the four sites, the nine profile stations are distributed in a grid pattern, where a 100 cm pit was dug at each station location and six TDR probes were inserted horizontally into the soil. The majority of probes were inserted at 10, 20, 30, 50, 70 and 100 cm depths in order to capture the change in soil moisture in the hydrologically dynamic layer. In some instances, soil and topographic conditions did not allow for the full 100 cm depth to be reached and the TDR probes were inserted at 10, 20, 30, 40, 50, 60 cm depths instead (see Table 2). All of the TDR profiles are connected to a data logger at the centre of the array at station 1. Each TDR array has an associated tipping bucket rain gauge and automated weather stations are associated with the TDR arrays located between K1 and K2 and at GR. The soil moisture data has been pre-processed to remove most erroneous measurements and when less than 72 temporally consecutive missing values were present, the data was infilled using linear interpolation (Kornelsen and Coulibaly, 2012) and/or the soil layer relative difference method if some values were missing between stations (Kornelsen and Coulibaly, 2012; Dumedah and Coulibaly, 2010). In addition to the Campbell Scientific datasets a Stevens Water Hydra Probe array is operated in conjunction with the CS616 array at Kelso 1 providing an independent soil moisture dataset for comparison/validation and additionally providing long term 5 cm soil moisture at half-hourly intervals.

All four sites are located on protected conservation land to ensure the safety and longevity of the monitoring network. The Kelso sites (K1 & K2) are located in the northern portion of the watershed in an area which is predominantly agricultural land. They have poorly drained clay loam soils and the terrain is generally flat with some hummocks and a few small gentle sloping hills at the edge of the site. The land-cover is predominantly meadow with some recently planted coniferous and aspen trees scattered throughout the site. The GR and OR sites are located in the Dundas Valley Conservation Area. The Dundas Valley is part of the Niagara Escarpment and is predominantly covered by mixed Carolinian forests, and fields. Both sites have silty loam soils with good drainage and moderate infiltration. OR is located in a reclaimed apple orchard which is covered by meadow vegetation and has sparse apple trees. The site covers the transition between a gentle north facing slope and a flat plateau. The GR site is located on mixed terrain and has steep and gentle slopes having mixed/pine forest covering most of the site with small open areas around the weather station and on the steep slopes. Figure 4 shows the terrain of each site and the locations of the soil moisture stations within each site.

The soil moisture arrays are supplemented with six weather stations and nine rain gauges distributed throughout the watershed. The weather stations are a mix of Campbell Scientific and HOBO stations, recording half-hourly observations of air temperature, relative humidity, vapour pressure, saturation vapour pressure, precipitation (rain only), incoming solar radiation, wind speed and wind direction. Additionally, evapotranspiration is calculated from the collected data using the Penman-Monteith equation. The weather/hydrometric stations were distributed to provide good characterization of the watershed with considerations given to accessibility and security. There are also 8 weather stations within or near the watershed which are operated by the Ontario Ministry of Natural Resources or Environment Canada, which are also shown on Fig. 1.

### 2.3 Campbell Scientific TDR and Stevens Hydra Probe comparison

At the K1 site, both CS616 TDR and Stevens Hydra Probes were installed in order to provide a comparison between the two data products. It must be noted that gravimetric sampling was not conducted regularly at this site in conjunction with automated measurements. Therefore, only a comparison between measurements can be made, which is summarized in Fig. 5. In general, the soil moisture data from the CS TDR and Hydra Probes follow similar temporal trends at all sites in terms of wetting and drying curves and rates. The positive differences in Fig. 5 indicate that the CS TDR records higher soil moisture values than the Hydra Probe, which is common amongst all depths. Overall small differences (less than 5% in average) is observed between the two records. The smallest differences between the two data sets occur at the 30 and 50 cm depths, whereas larger differences are observed between 10 and 20 cm depths. This is mostly due to the large variability of soil moisture in the top layers compared to deeper layers. Some larger differences between the two measurements occur at stations 3 and 4 at all depths (Fig. 5). This is in part due to the specific locations of the two stations (3 and 4).

At those two locations the CS TDR measurements show higher variability compared to other sites. However in general, the differences are mostly due to the noise in hourly data.

# 3 Methodology

## 3.1 Statistical methods

For both the analysis and manipulation of soil moisture data, and for ease of use/presentation the data is characterized using standard sample statistics. Herein, both spatial and temporal soil moisture statistics will be presented and so we will differentiate the statistics in terms of variability in both space and time.

Let $\theta_{ijk}$ be the soil moisture $\theta$ at station $i$ and time $k$ for the sampling depth $j$. The spatial mean soil moisture for a site $\overline{\theta_{jk}}$ can be calculated as:

$$\overline{\theta_{jk}} = \frac{1}{N_i} \sum_{i=1}^{N_i} \theta_{ijk} \tag{1}$$

where $N_i$ is the number of stations $i$ at which soil moisture is sampled for a given depth $j$. Similarly the daily mean soil moisture for a station $\overline{\theta_{ij}}$ is given as:

$$\overline{\theta_{ij}} = \frac{1}{M} \sum_{k=1}^{M} \theta_{ijk} \tag{2}$$

where $M$ is the number of hours (usually 24) over which the mean value is taken. The daily soil moisture for a site at a specific depth is given by:

$$\overline{\theta_j} = \frac{1}{N_i M} \sum_{i=1}^{N_i} \sum_{k=1}^{M} \theta_{ijk} = \frac{1}{N_i} \sum_{i=1}^{N_i} \overline{\theta_{ij}} \tag{3}$$

where the mean daily soil moisture for each station is first derived and the spatial mean is then calculated. For ease of consideration, the standard deviation and variance of soil moisture is only considered based on the second summation. Therefore the daily variance of a station is given by:

$$\sigma_{ij}^2 = \frac{1}{M-1}\sum_{k=1}^{M}\left(\theta_{ijk} - \overline{\theta_{jk}}\right)^2 \tag{4}$$

whereas the variance of the daily soil moisture at the entire site for depth $j$ is given by:

$$\sigma_j^2 = \frac{1}{N_i}\sum_{i=1}^{Ni}\left(\theta_{ij} - \overline{\theta_j}\right)^2 \tag{5}$$

where the variance determined in Eq. (4) is ignored when calculating the daily site variance in Eq. (5). The above equations can also be extended to apply to monthly soil moisture where daily soil moisture at a site/station is first calculated and Eqs. (2, 3) and (4, 5) are reapplied using $M$ as days instead of hours.

### 3.2 Temporal stability

The concept of temporal stability was first proposed by Vachaud et al. (1985) and is used to determine the temporal persistence of the spatial soil moisture pattern. Analysis of the temporal persistence leads to some understanding of the processes that influence the organized portion of the spatial soil moisture pattern. Temporal stability analysis is conducted using the parametric test of the relative differences, where the relative difference $\delta_{jk}$ at depth $j$ and time $k$ is given by:

$$\delta_{ijk} = \frac{\theta_{ijk} - \overline{\theta_{jk}}}{\overline{\theta_{jk}}} \tag{6}$$

In order to mitigate the effects of stochastic influences on the soil moisture pattern and the relative difference statistic, the mean and standard deviation can be calculated where the mean relative difference $\overline{\delta_{ij}}$ and its standard deviation $\sigma(\delta_{ij})$ are given by:

$$\overline{\delta_{ij}} = \frac{1}{M}\sum_{k=1}^{M}\delta_{ijk} \tag{7}$$

$$\sigma(\delta_{ij}) = \sqrt{\frac{1}{M-1}\sum_{k=1}^{M}\left(\delta_{ijk} - \overline{\delta_{ij}}\right)^2} \tag{8}$$

where the variable $M$ can be taken as a daily, monthly, annual or other value. It is common to express the mean relative difference based on the entire study period. A relative difference of zero refers to a station that is representative of the mean soil moisture value, where high and low values represent sites that are consistently wet or dry, respectively compared to the mean.

## 4 Results and discussion

The soil moisture in the Hamilton-Halton watershed follows a seasonal cycle, with temperature and precipitation patterns seen in Fig. 2 and seasonal mean soil moisture presented in Table 3. While the precipitation is relatively evenly distributed throughout the year, during the winter months there is little evapotranspiration and precipitation tends to accumulate on the surface as snow. The spring thaw results in strong wetting of the soil, until the late-spring and summer temperature increase causes a net dry-down of the soil. Thus, there are seasonal periods of wetting from the late fall to early spring months followed by a drying period from late spring to early fall. The notable exception to this pattern in Table 3 is the deep soil during the autumn which experiences a slight net loss from the previous season. Close analysis (results not shown) reveal this secondary dry-down is the result of dry autumns in 2007 and 2009 (Table 2) skewing the temporal statistics. The variability in the surface soil moisture dampened the impact of these dry years in the statistics of the upper soil layers. Since the soil moisture data of the McMaster Mesonet have been collected onward from 2006, the dataset covers several unseasonably wet and dry periods and numerous wetting and drying events, which makes the dataset especially useful for hydrological analysis.

The further soil moisture data analyses conducted herein are only for the 10, 20 and 50 cm depths using the data from the CS616 TDR probes, as soil moisture observations are available for every site and station at these depths. The following sections will present the results of the spatio-temporal and temporal stability analysis. First, the monthly mean and standard deviation will be discussed with links made to the local soil moisture state and variability as a result of local ground cover and topography. The temporal stability analysis will follow, with an analysis of the strength of the stability pattern and the time for spatial organization to return following a disturbance.

### 4.1 Spatio-temporal analysis

A time series of the mean daily soil moisture in the top 50 cm is shown in Fig. 6, along with the precipitation at each site. The horizontal lines show the mean soil moisture for the entire study period averaged over the top 50 cm of the soil profile. One standard deviation of the temporal mean is represented by the upper and lower horizontal lines, and one spatial standard deviation for each day is represented by the shaded area. As previously noted, the soil moisture exhibits seasonality, with dry periods during summers and recharge of the soil moisture during the winter and spring. The distribution of the soil moisture about the temporal mean shows the temporal soil moisture to be negatively skewed (GR = −0.89; OR = −0.97; K1 = −0.90; K2 = −1.02) largely resulting from presence of summer dry-down, particularly in 2007 and 2011, and the upper boundary imposed by saturation. The poor drainage and low infiltration of K1 and K2 results in longer periods near the saturation boundary, whereas GR and OR have higher infiltration and topographic runoff, resulting in a more rapid transition of the soil moisture state. The spatial variability tends to be relatively uniform through time at all sites, although this is somewhat visually masked by the vertical transitions in Fig. 6. The greatest spatial variability tends to occur during periods with little transitions, or the plateaus in Fig. 6. The greater variability during the non-transitional periods is the result of the spatial variability induced by geographic factors, such as depressions between hummucks at K1 and K2 storing water, or the redistribution of water to valleys at GR.

Since the soil moisture in the watershed exhibits seasonality the data have been aggregated on a monthly basis for the years 2007 to 2011 and analyzed as spatial soil moisture patterns. The seasonal (monthly) mean and seasonal (monthly) variance of soil moisture for each site can be seen in Fig. 7 as contour plots, which were created by interpolating the soil moisture values between points. For the purposes of making physical interpretation of the soil moisture patterns, the results will be presented as first an inter-site comparison making broad generalizations, and then intra-site comparisons making note of specific anomalies and patterns.

Both K1 and K2 have the most uniformly distributed soil moisture at all depths and are persistently wetter than the other sites. This results from the lower infiltration capacity and flat topography at this site. Also, the hummocky terrain provides many small depressions in which surface water is stored. OR also has a relatively uniform soil moisture pattern at all depths, although there is a marked spatial pattern at the 10 and 20 cm depths resulting from the sloping terrain. GR has the most variability in soil moisture pattern during all months resulting from the complex topography and vegetation. All sites experience the highest variability (standard deviation) during the month of January, which is believed to be the result of freeze-thaw processes with temperature fluctuations around 0 °C causing redistribution of soil moisture; although more work is required before definitive conclusions can be made. The lowest variability is during the spring season, when the soil is consistently wet due to snowmelt and low evapotranspiration. During the summer months, there is moderate variability, brought on by wetting and drying cycles.

In general, the results of the soil moisture analysis are consistent with previous studies (Famiglietti et al., 1998; Vivoni et al., 2008), which found that there tends to be low soil moisture values and high variability at the top of slopes and high soil moisture and low variability at the bottom of slopes, with moderate values mid-slope. This pattern was also present at K1 and K2, where there are few prominent terrain features, with the notable exceptions of a small embankment at the south-east of K1 and a hill in the north-east of K2. These features result in lower mean soil moisture, which is particularly prominent during the summer and fall months and result in the greatest contrast in standard deviations during the winter months. Unlike the findings of Mohanty and Skaggs (2001), this shows that even minor topographic variations at a site which is generally considered flat can impact the soil moisture spatial pattern in a consistent way. The slope pattern in Kelso is also consistent, although somewhat muted, to a depth of 50 cm, however it declines at 70 to 100 cm (results not shown). This pattern is also generally present at OR, with the exceptions of OR-1 which has high soil moisture and low variability but is located mid-slope. This anomaly results from a slight depression in the surface at OR-1 storing water. Similarly, OR-6 is located upslope and has lower mean and more highly variable soil moisture at 10 cm than expected. While consistent with the pattern described in Famiglietti et al. (1998) the soil moisture at OR-6 is extreme compared to OR-7/8 which are higher upslope. This pattern is thought to be the result of a footpath just above the OR-6 sensors, resulting in a discontinuity of the slope. Therefore, despite being lower on the slope than OR-7 and OR-8, this station has a smaller “effective” upslope area. While still present, the impact of the surface characteristics are not as prevalent at the 20 and 50 cm depth suggesting that, at lower depths, soil moisture is more representative of general patterns in the landscape. At GR, station 7 has high mean soil moisture and high variability during the spring and summer seasons to a depth of 50 cm, but has only moderate soil moisture during the winter and fall. The high variability at GR-7, which is located near the crown of a hill, is consistent with previous findings (Famiglietti et al., 1999). Similarly, the higher moisture content present in the valleys is also consistent with previous findings (Famiglietti et al.,

1999) suggesting a good quality of the Mesonet data and its ability to depict small scale soil moisture dynamics.

## 4.2 Temporal stability analysis

The temporal stability of a station refers to the position of a station relative to the mean soil moisture state at a particular site. It has often been noted that while absolute soil moisture changes, the ranking of soil moisture at a particular location with respect to the mean value is relatively constant (Vachaud et al., 1985; Martinez-Fernandez and Ceballos, 2003; Cosh et al., 2004; Vivoni et al., 2008), although there have also been findings where the opposite is true (Mohanty and Skaggs, 2001). Here, the temporal stability at each site has been analyzed on a seasonal (monthly) basis for the 10, 20 and 50 cm depths. The spatial patterns found are similar to the mean soil moisture patterns found in Fig. 7, and so will not be re-produced here. For the flat/gently sloping terrain at K1, K2 and OR the relative rank of each station remains generally consistent throughout time. There is some variability at the monthly scale, where some stations may change ranking with similar stations throughout the year, however, these stations tend to be similar in rank, and so despite absolute changes in rank, when the variability of these sites is considered the change is not thought to be meaningful. This conclusion has yet to be statistically verified and is left for future work as it is beyond the scope of this article. Unlike the other sites, there is a marked change in temporal rankings at GR throughout the year. With the exception of the month of January the ranks for all of the stations at GR have low variability, but shift significantly at the 10 and 20 cm depths. The greatest change occurs at GR-4, 6, and 7. During the winter and spring the downslope station (GR-4) is consistently the highest ranked station (wet), however, during the summer and fall months GR-4 becomes mid-ranked and is representative of the site mean soil moisture. The stations at GR-6 and GR-7 are ranked in the middle, being representative of the site mean, during the winter months, then become increasingly wet throughout the summer and transition to being mean representative again in October. The reasons for these transitions at GR are thought to be derived from the mixed vegetation at this site. Since the majority of soil moisture monitoring programs have been carried out in meadows and agricultural fields (Famiglietti et al., 1998, 1999; Brocca et al., 2007; Heathman et al., 2009; and others), GR offers unique insight the importance of higher density vegetation in determining the soil moisture spatial pattern. It has been shown that at small scales precipitation increases homogeneity with wetting, which is subsequently redistributed by topography, soil texture and evapotranspiration following wetting in areas with low tree density (Wilson et al., 2003; Famiglietti et al., 2008; Vivoni et al., 2008), and is consistent with results at K1, K2 and OR. However, GR is covered by a mix of forested areas and open meadows, resulting in vegetation causing a seasonal organization in soil moisture during wetting. The hill upon which GR-7, GR-6 and the GR weather station are located has little tree canopy cover, whereas all other stations at GR are at least partially covered, except for GR-4. The exposure of GR-7 resulted in less rain/snow interception causing a high mean relative difference and also resulted in the GR-7 station being more exposed to wind and sunlight causing high evaporation. Additionally, the effect of topographic redistribution gives the site high variability. The seasonality of the mean relative difference patterns shows the possibility of temporal instability in seasonal climates such as those present in Canada. The reason for the change is the transition of the dominant influence of the soil moisture pattern. During the winter months, when vegetation is dormant, topography is the greatest controlling influence in soil moisture distribution, whereas during the spring and summer the vegetation canopy increases interception which dominates the soil moisture spatial distribution at GR. Therefore, even at a depth of 50 cm the vegetation pattern had a strong influence on the soil moisture pattern.

The fundamental concept of temporal stability is the persistence of the relative spatial pattern of soil moisture. However, it is known that precipitation has a homogenizing effect on the soil moisture pattern, and can disrupt the temporal stability pattern at all scales (Wilson et al., 2003; Famiglietti et al., 2008). In order to provide a preliminary assessment of the impact of precipitation in the Hamilton-Halton watershed four rain storms were selected to analyze the length of interruption of the temporal stability pattern and to provide insight as to the duration required for the dominant soil moisture pattern to re-emerge. The four rain events were selected based on two primary criteria: (i) significant rainfall being present at both Kelso (K1) and Dundas Valley (GR & OR) and (ii) a sufficient period without rain is present both prior to and following the rain event so as to allow for the presence of a stable soil moisture pattern before and after the rain. The details of the four selected storms can be found in Table 4, and the relative difference for storm 2 is shown in Fig. 8. Only storm 2 at 10 cm is presented herein for brevity. The impact of the rain is monitored at K1, GR and OR, where K2 is ignored because of the close proximity and similar topography to K1.

Due to the dry conditions prior to rainfall and the sloping topography, rain event 1 did not have a distinguishable impact on the soil moisture pattern at GR or OR, however it did cause noticeable wetting at K1. Despite this, the impact was not strong enough to disrupt the persistence of the soil moisture rank pattern. While some change occurred immediately following the precipitation, the peak of the impact at K1 occurred 24 to 40 h following the rain event as ponded water slowly infiltrated the poorly drained soil. Rain storm 2 added significantly more water to the soil than the other storms and had a strong wetting effect at all sites, with the greatest impact at the 20 cm depth. At K1 the storm caused wetting of the already moist soil, but did not disrupt the relative ranks of the spatial soil moisture pattern. Due to the relatively higher clay content and flat topography the impact of the rain also persisted longer at K1 compared to the other sites, with the impact at some stations lingering for as many as 6 days after the rainfall. Similarly, at OR the rain caused a large increase in the amount of soil moisture but did not lead to the homogenization of soil moisture, and thus the persistent pattern was still present. At GR, stations 5 and 7, which are under dense vegetation and on the hill-top, respectively, experienced some wetting but were less impacted than other stations and were stable as relatively dry sites during that time period. The remaining GR sites, which were still wet from a previous rainfall, became homogenous disrupting the temporal stability pattern. The relative soil moisture pattern began to re-emerge within 18 to 24 h following the peak rainfall. The impact of the rainfall lingered for the least amount of time at stations 2, 4 and 9, which are located on upper slopes for stations 2 and 9, and having little canopy at station 4. This also shows the importance of relative dominance of contributing influences to the soil moisture pattern, where dense vegetation excludes even heavy rainfall, and moderate tree canopy can cause the added water to be stored in the soil for longer periods of time. Also significant, is the impact of the rainfall and the stability pattern at station 4, which is topographically the lowest station but dries more quickly than stations 1 and 3 which have more canopy cover. At all sites the spatial pattern had the greatest disruption which was sustained for the longest period of time at the 20 cm depth. The lack of surface evaporation and already greater homogeneity at this depth caused the effect of the precipitation to linger for approximately 2 days longer than at the 10 cm depth. While there was some wetting, the rainfall did not affect the spatial soil moisture pattern at 50 cm at any site. The rainfall from events 3 and 4 did result in an increase in soil moisture but was not strong enough to impact the strength of the spatial soil moisture pattern at any site or depth with the exception of OR at 20 cm. The rain from event 3 occurred during the spring months, where the soil moisture at 20 cm at OR was already very moist and so additional water did disrupt the persistence of the spatial pattern, but more due to the already high water content of the soil at that depth rather than the impact of that particular rainfall.

These results lead to several insights about the nature of temporal stability following rain. It should first be noted, that without the soil being wet prior to the addition of water, the temporal stability of the soil moisture was not impacted without the addition of a considerable amount of rain (> 20 mm). The normal rainfall amounts for the watershed (5 to 10 mm) did increase the soil water content but did not cause enough homogenization to affect the temporal (rank) stability pattern, even at the flat and poorly drained Kelso site. Also important is the impact of topography and vegetation as was best noted at the GR site. Dense vegetation resulted in high interception leaving station 5 persistently dry, whereas station 4, despite being lowest in elevation and being mid-slope in a valley, has no tree canopy cover and so while its rank was impacted by rainfall, the higher potential for evapotranspiration from the field vegetation and sun penetration caused that station to recover its relative rank with only a short delay.

## 5 Conclusions

The McMaster Mesonet was introduced and spatio-temporal and temporal stability analysis carried out in order to characterize the soil moisture patterns representative of the Mesonet datasets. The McMaster Mesonet consists primarily of the infrastructure necessary to monitor hourly soil moisture profiles using a high spatial resolution TDR array at four sites, as well as associated hydro-meteorological stations. The sites represent different topographies and vegetation covers as well as providing some insight into the seasonal patterns of soil moisture experienced in the Canadian climatic context.

Analysis of the data reveals a moderately strong organized soil moisture pattern which is temporally persistent on a seasonal basis. The spatial soil moisture distribution was dominated, at a seasonal scale, by the change in vegetation canopy and the transition between net-gain and net-loss of soil moisture brought on by climate processes. At the daily-weekly scale, topography, vegetation canopy cover and precipitation dominated the spatial distribution of soil moisture. The spatial pattern at sub-seasonal scales was persistent in most conditions, unless a substantial rainfall/snowmelt resulted in homogenization of the soil moisture. Following the disturbance by precipitation, the relative soil moisture pattern re-emerged after 18 to 24 h of drying and the moisture added by the precipitation was removed within 4 to 7 days. At the sub-seasonal time scale, soil moisture variability was the greatest at a depth of 10 cm, and was lowest at a depth of 50 cm. The spatial pattern of soil moisture at a depth of 20 cm was more representative of mean topography, where the influence of hummocks and small depressions at the surface was not as prevalent.

The long term high-spatial resolution hourly soil moisture profiles recorded by the McMaster Mesonet can provide insights into the nature of this important hydrological state variable. Future work will use data from the McMaster Mesonet for data assimilation to improve hydrological forecasts, validation of high resolution remote sensing soil moisture products and to study the complex interactions between climate, soil, topography and vegetation.

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**Table 1.** Climatic conditions based on Brittania weather station (located at the centre of the watershed) and the Hamilton Airport weather station (approx. 5 km south of watershed).

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hamilton Airport (1971–2000) | | | | | | | | | | | | | |
| Daily Max Temp (˚C) | −2.2 | −1.2 | 4.0 | 11.2 | 18.5 | 23.7 | 26.3 | 25.1 | 20.7 | 13.8 | 7.0 | 0.9 | 12.3 |
| Daily Min Temp (˚C) | −9.7 | −9.1 | −4.5 | 1.2 | 7.3 | 12.4 | 15.1 | 14.5 | 10.2 | 4.4 | −0.4 | −6.2 | 2.9 |
| Daily Mean Temp (˚C) | −6 | −5.2 | −0.3 | 6.3 | 12.9 | 18.0 | 20.8 | 19.8 | 15.5 | 9.1 | 3.3 | −2.7 | 7.6 |
| Rainfall (mm) | 29.5 | 25.7 | 48.6 | 69.6 | 75.0 | 83.9 | 86.5 | 80.6 | 82.1 | 71.6 | 68.1 | 43.7 | 764.8 |
| Precipitation (mm) | 65.8 | 55.3 | 74.8 | 78.0 | 75.6 | 83.9 | 86.5 | 80.6 | 82.1 | 72.5 | 78.6 | 76.6 | 910.1 |
| Mesonet – Brittania (2007) | | | | | | | | | | | | | |
| Daily Max Temp (˚C) | −0.3 | −4.9 | 4.2 | 9.2 | 20.3 | 26.0 | 26.1 | 26.5 | 23.4 | 17.8 | 5.5 | −0.4 | 12.8 |
| Daily Min Temp (˚C) | −7.4 | −13.1 | −4.6 | 1.4 | 7.6 | 13.4 | 13.7 | 15.1 | 10.9 | 8.2 | −1.9 | −6.3 | 3.1 |
| Daily Mean Temp (˚C) | −3.8 | −9.0 | −0.2 | 5.3 | 14.0 | 19.7 | 19.9 | 20.8 | 17.2 | 13.0 | 1.8 | −3.3 | 7.9 |
| Precipitation (mm) | 51.8 | 10.6 | 57.8 | 70.8 | 46.0 | 43.4 | 16.8 | 28.0 | 25.6 | 50.4 | 66.6 | 62.0 | 529.8 |
| Mesonet – Brittania (2008) | | | | | | | | | | | | | |
| Daily Max Temp (˚C) | 0.5 | −1.3 | 2.0 | 14.0 | 16.3 | 23.7 | 26.1 | 22.3 | 21.1 | 13.4 | 5.7 | 0.0 | 12.0 |
| Daily Min Temp (˚C) | −6.4 | −9.9 | −6.4 | 2.7 | 5.3 | 13.6 | 15.2 | 7.3 | 10.7 | 3.2 | −1.4 | −8.2 | 2.2 |
| Daily Mean Temp (˚C) | −2.9 | −5.6 | −2.2 | 8.3 | 10.8 | 18.7 | 20.7 | 14.8 | 15.9 | 8.3 | 2.2 | −4.1 | 7.1 |
| Precipitation (mm) | 58.0 | 64.6 | 49.0 | 50.0 | 53.8 | 108.6 | 143.2 | 120.0 | 102.2 | 36.6 | 77.2 | 100.6 | 963.8 |
| Mesonet – Brittania (2009) | | | | | | | | | | | | | |
| Daily Max Temp (˚C) | −5.2 | 0.8 | 5.0 | 11.8 | 18.1 | 21.9 | 23.1 | 25.1 | 21.1 | 11.6 | 9.1 | −0.2 | 11.9 |
| Daily Min Temp (˚C) | −13.5 | −8.8 | −4.5 | 1.8 | 6.5 | 11.4 | 13.2 | 14.7 | 10.5 | 3.7 | 1.0 | −6.3 | 2.5 |
| Daily Mean Temp (˚C) | −9.4 | −4.0 | 0.3 | 6.8 | 12.3 | 16.7 | 18.2 | 19.9 | 15.8 | 7.7 | 5.0 | −3.3 | 7.2 |
| Precipitation (mm) | 17.8 | 71.2 | 63.0 | 137.6 | 50.0 | 52.8 | 97.4 | 120.8 | 31.4 | 82.9 | 32.5 | 91.6 | 849.0 |
| Mesonet – Brittania (2010) | | | | | | | | | | | | | |
| Daily Max Temp (˚C) | −2.6 | −0.9 | 8.2 | 15.9 | 20.4 | 23.1 | 28.0 | 26.5 | 20.3 | 14.1 | 7.7 | −1.8 | 13.3 |
| Daily Min Temp (˚C) | −8.8 | −7.4 | −1.1 | 3.8 | 8.9 | 13.6 | 16.4 | 15.7 | 10.2 | 4.6 | −1.1 | −7.2 | 4.0 |
| Daily Mean Temp (˚C) | −5.7 | −4.1 | 3.6 | 9.8 | 14.7 | 18.4 | 22.2 | 21.1 | 15.2 | 9.4 | 3.3 | −4.5 | 8.6 |
| Precipitation (mm) | 20.1 | 19.0 | 91.2 | 48.6 | 55.2 | 138.6 | 127.0 | 39.4 | 106.8 | 73.0 | 129.0 | 31.3 | 897.2 |
| Mesonet – Brittania (2011) | | | | | | | | | | | | | |
| Daily Max Temp (˚C) | −3.8 | −1.2 | 3.0 | 10.6 | 17.7 | 23.3 | 29.6 | 26.5 | 21.7 | 14.5 | 10.3 | 3.5 | 13.0 |
| Daily Min Temp (˚C) | −11.9 | −10.2 | −5.8 | 1.2 | 8.4 | 12.5 | 16.7 | 15.0 | 11.3 | 5.5 | 2.0 | −3.6 | 3.4 |
| Daily Mean Temp (˚C) | −7.8 | −5.7 | −1.4 | 5.9 | 13.0 | 17.9 | 23.1 | 20.8 | 16.5 | 10.0 | 6.2 | 0.0 | 8.2 |
| Precipitation (mm) | 24.4 | 34.2 | 87.0 | 100.6 | 142.2 | 54.0 | 12.0 | 86.4 | 74.2 | 125.2 | 82.6 | 68.0 | 890.8 |
| Mesonet – Brittania (2007–2011) | | | | | | | | | | | | | |
| Daily Max Temp (˚C) | −2.3 | −1.5 | 4.5 | 12.3 | 18.6 | 23.6 | 26.6 | 25.4 | 21.5 | 14.3 | 7.7 | 0.2 | 12.6 |
| Daily Min Temp (˚C) | −9.6 | −9.9 | −4.5 | 2.2 | 7.3 | 12.9 | 15.0 | 13.6 | 10.7 | 5.0 | −0.3 | −6.3 | 3.0 |
| Daily Mean Temp (˚C) | −5.9 | −5.7 | 0.0 | 7.2 | 13.0 | 18.3 | 20.8 | 19.5 | 16.1 | 9.7 | 3.7 | −3.0 | 7.8 |
| Precipitation (mm) | 34.4 | 39.9 | 69.6 | 81.5 | 69.4 | 79.5 | 79.3 | 78.9 | 68.0 | 73.6 | 77.6 | 70.7 | 826.1 |

**Table 2.** McMaster Mesonet site and station description.

| Site name & description | Station | Probe depths (cm) | Station description |
|---|---|---|---|
| **Orchard – Dundas Valley** | 1 | 10, 20, 30, 40, 50, 60 | Clear sky, side-slope |
| Soil Texture: silt loam | 2 | 10, 20, 30, 50, 70, 100 | Partial canopy cover, downslope |
| Vegetation: short grass | 3 | 10, 20, 30, 40, 50, 60 | Clear sky, downslope |
| Terrain: gentle slopes, hill-slope | 4 | 10, 20, 30, 50, 70, 100 | Clear sky, downslope |
| Drainage: soil drains well | 5 | 10, 20, 30, 50, 70, 100 | Clear sky, side-slope |
| Hydrology: moderate infiltration when wet | 6 | 10, 20, 30, 40, 50, 60 | Partial canopy cover, upslope |
|  | 7 | 10, 20, 30, 40, 50, 60 | Clear sky, upslope |
|  | 8 | 10, 20, 30, 50, 70, 100 | Under tree canopy, upslope |
|  | 9 | 10, 20, 30, 40, 50, 60 | Clear sky, side slope |
| **Governor Road – Dundas Valley** | 1 | 10, 20, 30, 50, 70, 100 | Clear sky, close to tree, mid-elevation |
| Soil Texture: silt loam | 2 | 10, 20, 30, 40, 50, 60 | Canopy cover, mixed forest, side sloping |
| Vegetation: mixed forest; generally pine | 3 | 10, 20, 30, 40, 50, 60 | Partial canopy cover, in valley |
| Terrain: gentle and steep slopes | 4 | 10, 20, 30, 40, 50, 60 | Clear sky, close to tree, uphill |
| Drainage: soil drains well | 5 | 10, 20, 30, 40, 50, 60 | Dense canopy cover, mid-elevation |
| Hydrology: moderate infiltration when wet | 6 | 10, 20, 30, 40, 50, 60 | Partial canopy cover, down-hill |
|  | 7 | 10, 20, 30, 40, 50, 60 | Clear sky, uphill, upslope |
|  | 8 | 10, 20, 30, 50, 70, 100 | Canopy cover, mixed forest, upslope valley |
|  | 9 | 10, 20, 30, 40, 50, 60 | Canopy cover, mixed forest, side valley |
| **Kelso 1** | 1 | 10, 20, 30, 50, 70, 100 | Clear sky, tall grass, mid elevation |
| Soil Texture: clay loam | 2 | 10, 20, 30, 50, 70, 100 | Clear sky, tall grass, low elevation |
| Vegetation: short grass (light vegetation) | 3 | 10, 20, 30, 50, 70, 100 | Clear sky, tall grass, high elevation |
| Terrain: generally flat | 4 | 10, 20, 30, 50, 70, 100 | Clear sky, tall grass, high elevation |
| Drainage: is imperfect and poor | 5 | 10, 20, 30, 50, 70, 100 | Clear sky, short grass, mid elevation |
| Hydrology: slow to very slow infiltration when wet | 6 | 10, 20, 30, 40, 50, 60 | Clear sky, short grass, mid elevation |
|  | 7 | 10, 20, 30, 40, 50, 60 | Clear sky, short grass, low elevation |
|  | 8 | 10, 20, 30, 40, 50, 60 | Clear sky, short grass, mid elevation |
|  | 9 | 10, 20, 30, 40, 50, 60 | Clear sky, tall grass, high elevation |
| **Kelso 2** | 1 | 10, 20, 30, 40, 50, 60 | Clear sky, short grass, low elevation |
| Soil Texture: clay loam | 2 | 10, 20, 30, 50, 70, 100 | Clear sky, tall grass, high elevation |
| Vegetation: short grass (light-to-dense vegetation) | 3 | 10, 20, 30, 50, 70, 100 | Clear sky, tall grass, high elevation |
| Terrain: generally flat | 4 | 10, 20, 30, 50, 70, 100 | Clear sky, tall grass, mid elevation |
| Drainage: is imperfect and poor | 5 | 10, 20, 30, 40, 50, 60 | Clear sky, short grass, mid elevation |
| Hydrology: slow to very slow infiltration when wet | 6 | 10, 20, 30, 40, 50, 60 | Clear sky, dense grass, low elevation |
|  | 7 | 10, 20, 30, 50, 70, 100 | Clear sky, dense grass, low elevation |
|  | 8 | 10, 20, 30, 50, 70, 100 | Clear sky, dense grass, mid elevation |
|  | 9 | 10, 20, 30, 50, 70, 100 | Clear sky, dense grass, high elevation |

**Table 3.** Mean soil moisture for Winter (December, January, February), Spring (March, April, May), Summer (June, July, August) and Fall (September, October, November), and the average change between seasons at each site and depth.

Orchard

| | Winter | | Spring | | Summer | | Autumn | |
|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Mean | Change | Mean | Change | Mean | Change | Mean | Change |
| 10 | 0.30 | 0.00 | 0.33 | 0.03 | 0.27 | −0.06 | 0.30 | 0.02 |
| 20 | 0.33 | 0.03 | 0.34 | 0.01 | 0.29 | −0.06 | 0.30 | 0.01 |
| 30 | 0.35 | 0.04 | 0.36 | 0.01 | 0.31 | −0.05 | 0.31 | 0.00 |
| 40 | 0.36 | 0.04 | 0.37 | 0.01 | 0.33 | −0.04 | 0.33 | 0.00 |
| 50 | 0.37 | 0.05 | 0.37 | 0.01 | 0.33 | −0.04 | 0.32 | −0.01 |
| 60 | 0.39 | 0.04 | 0.39 | 0.01 | 0.36 | −0.03 | 0.35 | −0.02 |
| 70 | 0.37 | 0.05 | 0.38 | 0.01 | 0.34 | −0.04 | 0.32 | −0.02 |
| 100 | 0.38 | 0.05 | 0.39 | 0.01 | 0.36 | −0.03 | 0.33 | −0.03 |

Governor Road

| | Winter | | Spring | | Summer | | Autumn | |
|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Mean | Change | Mean | Change | Mean | Change | Mean | Change |
| 10 | 0.28 | 0.02 | 0.30 | 0.02 | 0.24 | −0.06 | 0.26 | 0.02 |
| 20 | 0.31 | 0.04 | 0.32 | 0.01 | 0.26 | −0.07 | 0.26 | 0.01 |
| 30 | 0.32 | 0.05 | 0.33 | 0.01 | 0.27 | −0.07 | 0.27 | 0.00 |
| 40 | 0.33 | 0.06 | 0.34 | 0.01 | 0.27 | −0.07 | 0.27 | 0.00 |
| 50 | 0.34 | 0.06 | 0.35 | 0.01 | 0.29 | −0.07 | 0.28 | −0.01 |
| 60 | 0.35 | 0.06 | 0.35 | 0.01 | 0.30 | −0.05 | 0.29 | −0.01 |
| 70 | 0.39 | 0.05 | 0.40 | 0.01 | 0.35 | −0.05 | 0.33 | −0.02 |
| 100 | 0.39 | 0.06 | 0.39 | 0.00 | 0.35 | −0.04 | 0.33 | −0.02 |

Kelso 1

| | Winter | | Spring | | Summer | | Autumn | |
|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Mean | Change | Mean | Change | Mean | Change | Mean | Change |
| 10 | 0.32 | 0.03 | 0.35 | 0.03 | 0.24 | −0.11 | 0.29 | 0.05 |
| 20 | 0.37 | 0.06 | 0.38 | 0.01 | 0.28 | −0.10 | 0.30 | 0.03 |
| 30 | 0.38 | 0.05 | 0.39 | 0.01 | 0.31 | −0.08 | 0.32 | 0.01 |
| 40 | 0.38 | 0.05 | 0.39 | 0.01 | 0.32 | −0.07 | 0.32 | 0.01 |
| 50 | 0.38 | 0.05 | 0.39 | 0.01 | 0.32 | −0.07 | 0.33 | 0.01 |
| 60 | 0.38 | 0.05 | 0.39 | 0.01 | 0.34 | −0.05 | 0.33 | 0.00 |
| 70 | 0.37 | 0.04 | 0.38 | 0.01 | 0.34 | −0.05 | 0.33 | −0.01 |
| 100 | 0.35 | 0.02 | 0.37 | 0.01 | 0.35 | −0.02 | 0.34 | −0.01 |

Kelso 2

| | Winter | | Spring | | Summer | | Autumn | |
|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Mean | Change | Mean | Change | Mean | Change | Mean | Change |
| 10 | 0.36 | 0.07 | 0.38 | 0.02 | 0.25 | −0.14 | 0.29 | 0.05 |
| 20 | 0.38 | 0.07 | 0.39 | 0.00 | 0.29 | −0.10 | 0.31 | 0.02 |
| 30 | 0.39 | 0.06 | 0.40 | 0.00 | 0.33 | −0.07 | 0.34 | 0.01 |
| 40 | 0.39 | 0.04 | 0.40 | 0.00 | 0.35 | −0.05 | 0.35 | 0.01 |
| 50 | 0.39 | 0.05 | 0.39 | 0.00 | 0.34 | −0.05 | 0.34 | 0.00 |
| 60 | 0.37 | 0.04 | 0.38 | 0.01 | 0.34 | −0.04 | 0.34 | 0.00 |
| 70 | 0.37 | 0.04 | 0.38 | 0.01 | 0.34 | −0.04 | 0.33 | 0.00 |
| 100 | 0.37 | 0.03 | 0.37 | 0.00 | 0.34 | −0.03 | 0.33 | −0.01 |

**Table 4.** Characteristics of analyzed rain events. If a rain event is broken into two distinct rainfalls, the amount of rain in each is separated, and the duration is separated as first rainfall duration, gap length, and second rainfall duration.

| Rain event | Date and time | Amount of rain (mm) | Duration (h) |
|---|---|---|---|
| | Kelso (K1) | | |
| 1 | 11 Jul 2009 – 09:00–11:00 | 6.2 | 3 |
| 2 | 28–29 Aug 2009 – 22:00–11:00 | 22.1 / 0.1 | 8 / 5 / 1 |
| 3 | 15–16 Mar 2011 – 23:00–10:00 | 6.1 | 12 |
| 4 | 3 Aug 2011 – 03:00–22:00 | 8.6 / 1.6 | 4 / 10 / 6 |
| | Dundas Valley (GR & OR) | | |
| 1 | 11 Jul 2009 – 09:00–14:00 | 9.0 / 0.1 | 2 / 1 / 1 |
| 2 | 28–29 Aug 2009 – 22:00–20:00 | 32.2 / 3.2 | 11 / 11 / 1 |
| 3 | 15–16 Mar 2011 – 22:00–10:00 | 4.8 | 13 |
| 4 | 03 Aug 2011 – 14:00–24:00 | 1.6 / 1.0 | 2 / 3 / 6 |

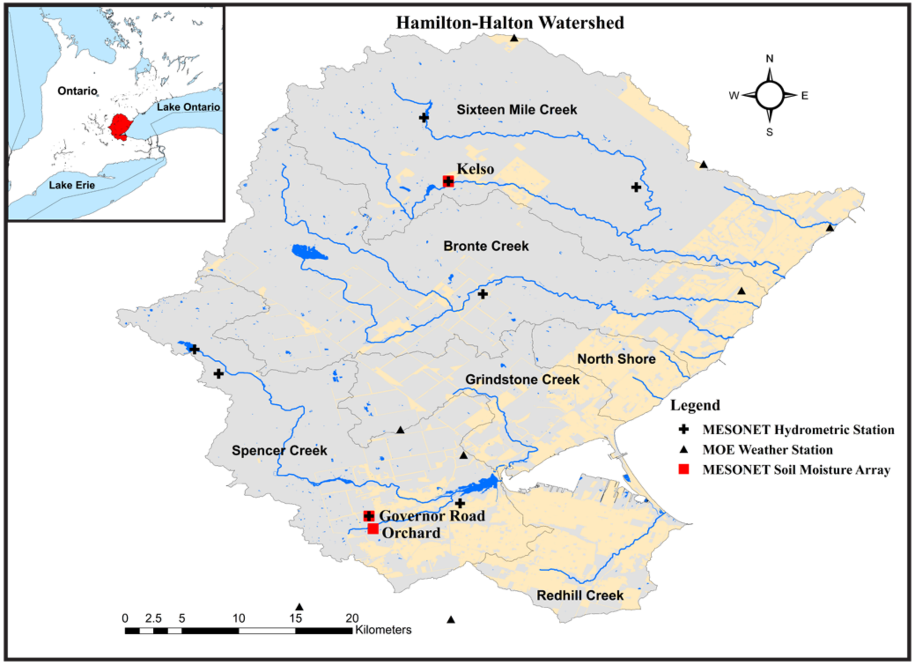

**Fig. 1.** Location map of the Hamilton-Halton Watershed including sub-watersheds and the locations of the soil moisture arrays and hydro-meteorological stations.

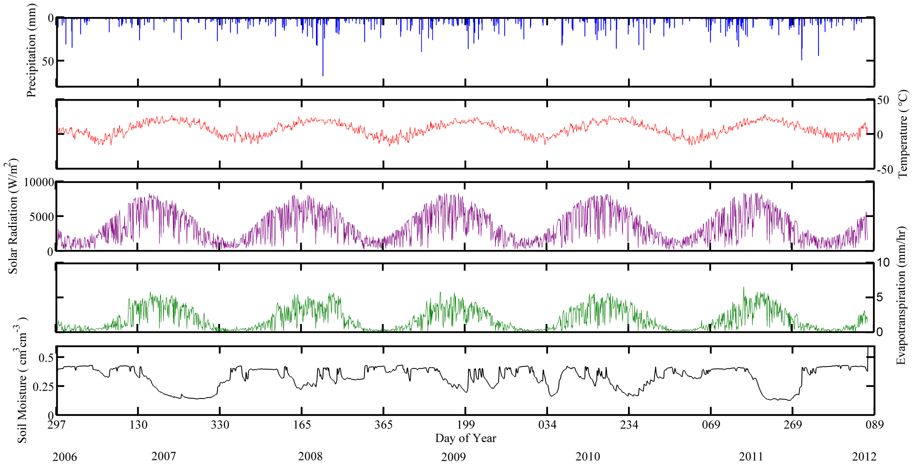

**Fig. 2.** Daily time series plot of 10 cm site averaged soil moisture from K1 and daily time series of meteorological data collected at Kelso.

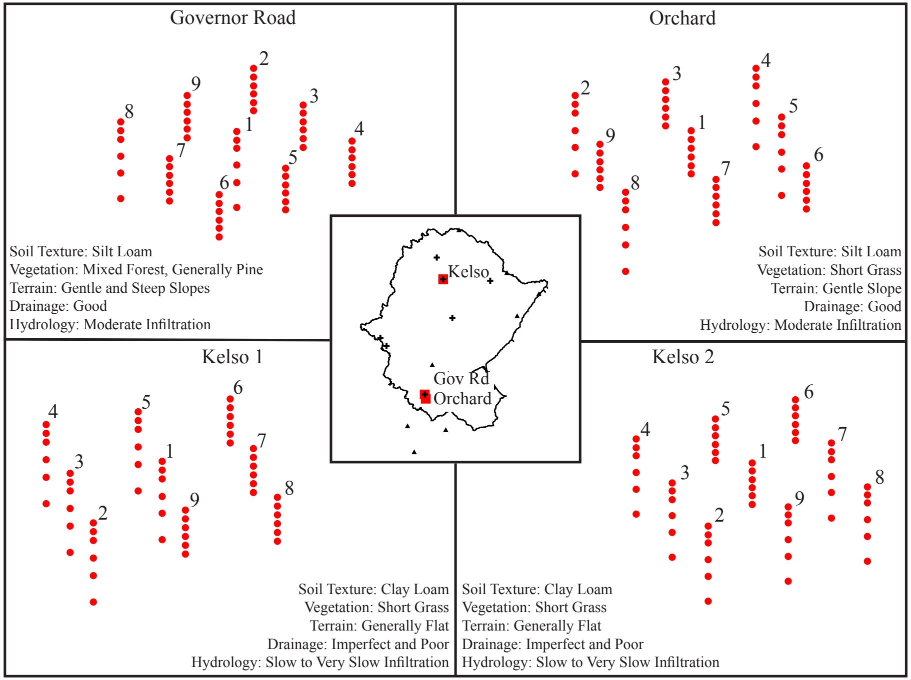

**Fig. 3.** Three dimensional schematic representation of the McMaster Mesonet. Note: The vertical dimensions are to scale, whereas spatial dimensions are not (see Fig. 4).

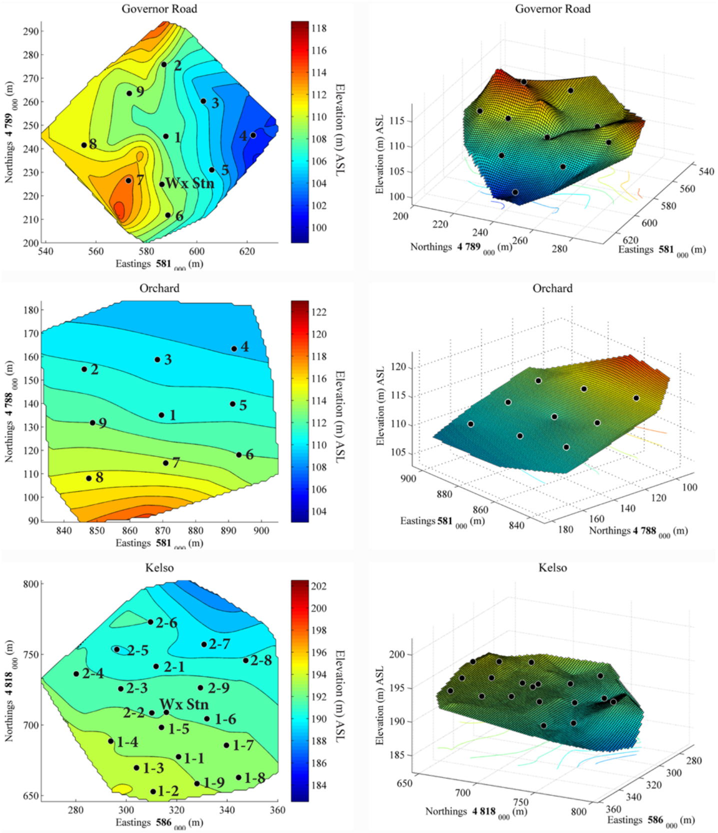

**Fig. 4.** Topography and layout of the soil moisture arrays at GR (top), OR (middle) and K1/K2 (bottom) as contour plots (left) and surface renderings (right). Topographic data were collected with an Ashtech MM100 GPS and have an approximate horizontal RMSE of 20 cm and vertical RMSE of 50 cm. Note: Surface and contour plots have different orientations to enhance the visual interpretation of the surface plot.

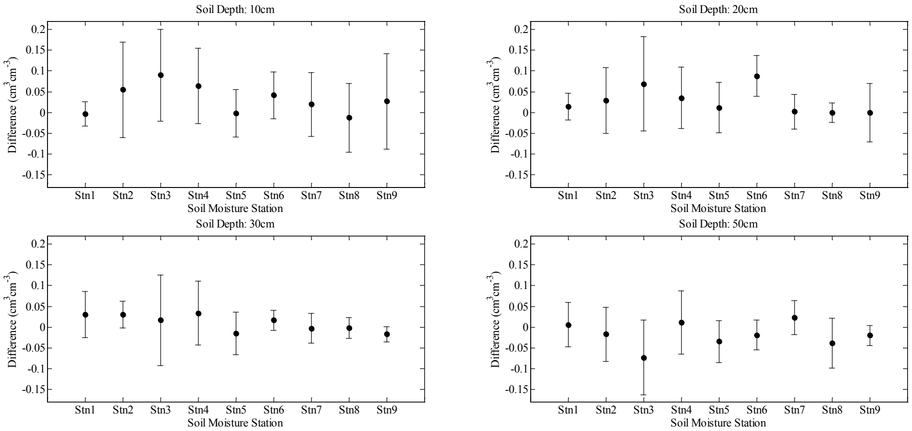

**Fig. 5.** Mean difference between Campbell Scientific CS616 TDR and Stevens Water Hydra Probe hourly soil moisture values at K1 from 2007 to 2011. The error bars represent one standard deviation.

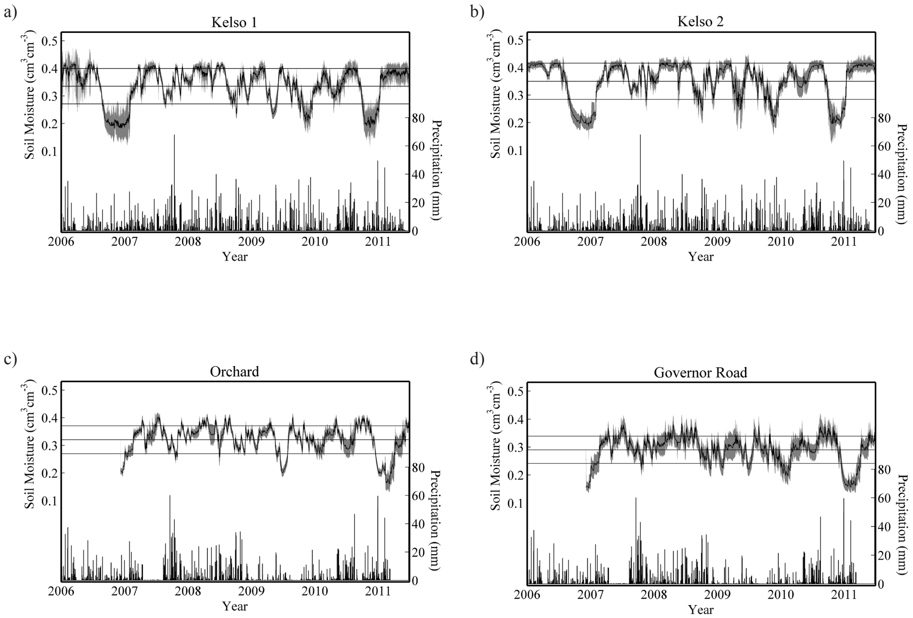

**Fig. 6.** Daily timeseries of mean soil moisture in the top 50 cm (black line) and precipitation (bars) for the McMaster Mesonet. The middle horizontal lines represent the mean of all observations at each site and one standard deviation, whereas the gray shaded area represents the spatial standard deviation for each sampling day.

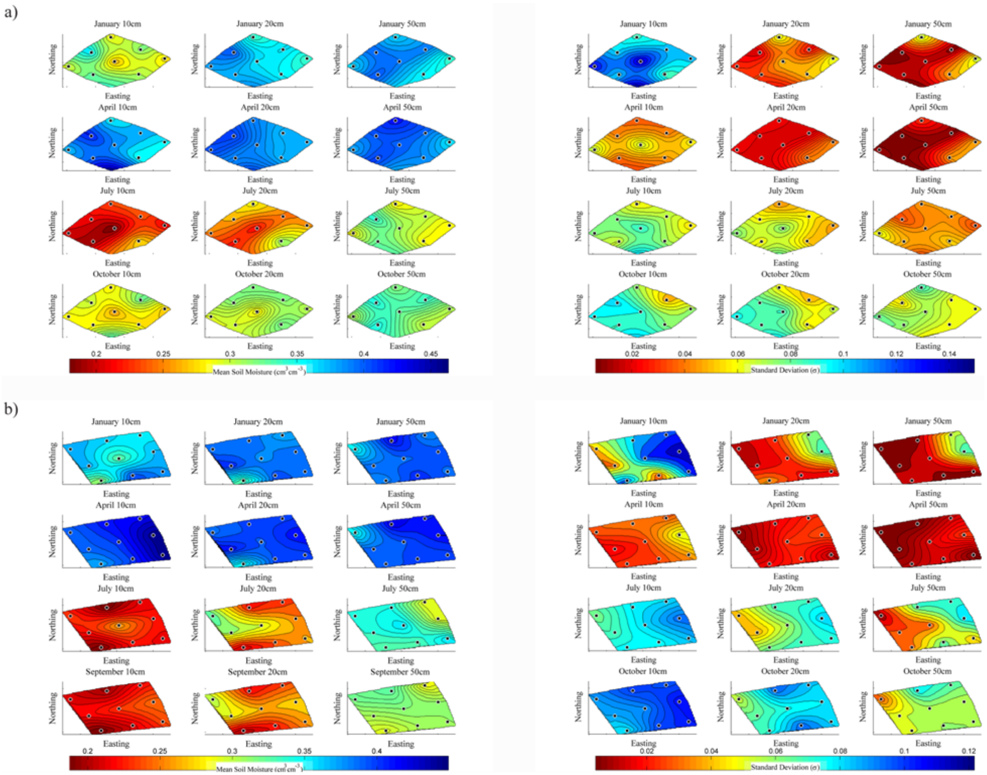

**Fig. 7.** Seasonal (monthly) mean soil moisture (left) and standard deviation (right) contour plots for **(a)** K1, **(b)** K2, **(c)** OR and **(d)** GR. The contour plots are created by interpolating the observed soil moisture and standard deviations spatially between points.

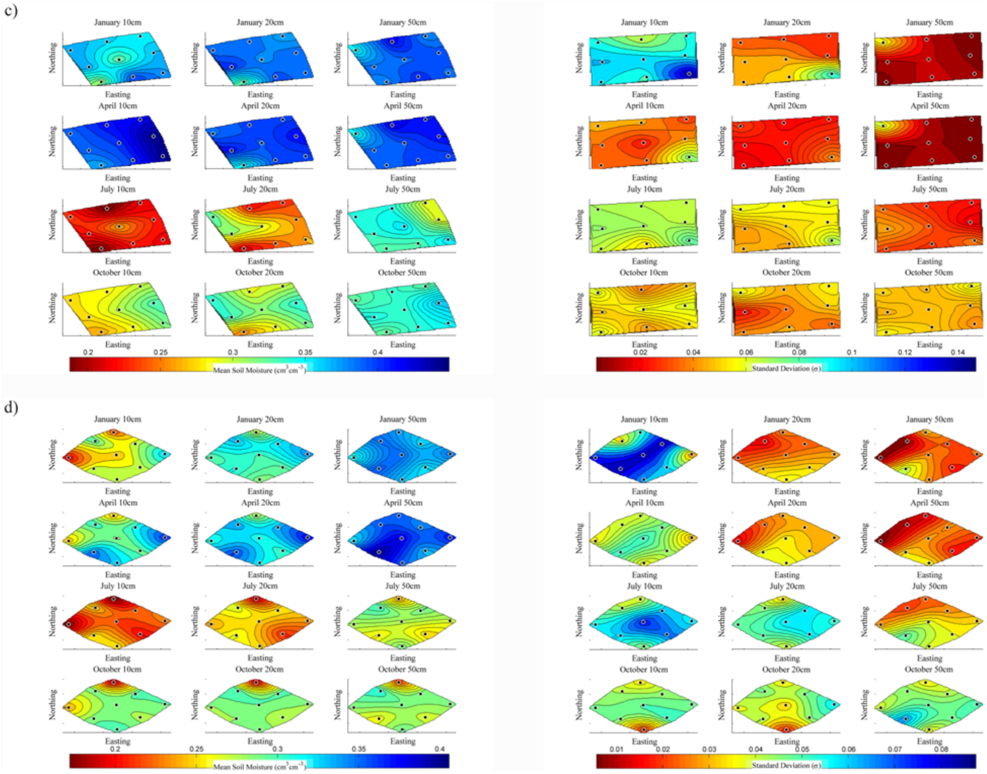

**Fig. 7.** Continued.

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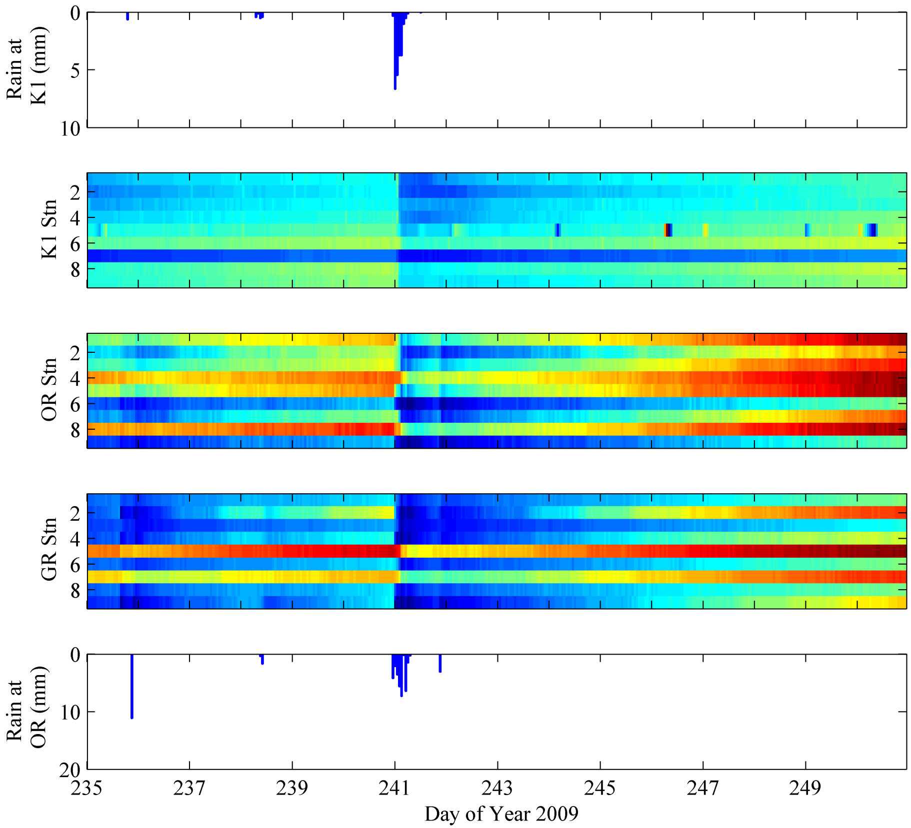

**Fig. 8.** Analysis of the mean relative difference before and after rain event 2 at a depth of 10 cm at K1, OR and GR. The colour scale changes from red (dry) to blue (wet) where mean soil moisture values ($\delta_{jk} = 0$) is cyan. For visual interpretation the colourmap is stretched for each image and colour values are relative.