Specific Conductance as a Tracer of Preferential Flow in a Subsurface-Drained Field

Erik A. Smith* and Paul D. Capel

Specific conductance (SC), soil volumetric water content (VWC), and discharge were monitored on a subsurface agricultural drain for a 2-yr period (2007–2008) to differentiate preferential flow paths from matrix flow paths. A major observation from the 2-yr period was the fast SC decrease after relatively small rainfall events, often <5 mm. A total of 25 paired rainfall–SC events were classified, with an average preferential flow onset time (from the event start) after 1.7 h and maximum preferential flow after 2.4 h. A specific conductance end-member mixing analysis (SC-EMMA) was used to determine the volume of water that infiltrated through preferential flow pathways. The SC-EMMA was used for 20 of the 25 paired rainfall–SC events; of the 20 classified events, the maximum preferential flow ranged from 11 to 75% of the total subsurface drain flow, with a mean maximum preferential flow of 31%. Overall, SC-EMMA illustrated that a significant portion of the subsurface drain discharge can be attributed to preferential flow, mainly through macropores or other largely open preferential flow pathways. The other primary mechanism, antecedent moisture conditions shifts, could only be shown for four of the 25 classified events. Specific conductance as a tracer of preferential flow was shown to be an effective tool for distinguishing preferential flow to subsurface drains. Even during relatively dry periods, the SC had a substantial decrease shortly after a rainfall event contrary to the conventional idea that macropore flow starts only after all the smaller pores are saturated and surface ponding begins to occur.

Abbreviations: EMMA, end-member mixing analysis; ET, evapotranspiration; SC, specific conductance; SFIR, South Fork Iowa River; VWC, volumetric water content.

Throughout the Upper Midwest of the United States, covering a vast region from eastern North Dakota to Ohio, the last glacial advances left a large province of poorly drained soils, characterized by isolated wetland basins (Pavelis, 1987; Blann et al., 2009). The installation of artificial surface and subsurface drainage networks, a common practice for removing excess water from agricultural fields, has allowed these poorly drained soils to become productive agricultural land. Artificial subsurface drainage allows rainfall to move quickly through the soil to the stream and, in the process, can transport nutrients, pesticides, and other agriculture-related chemicals (Schilling and Helmers, 2008; Tomer et al., 2008; Qi et al., 2011; Christianson and Harmel, 2015; King et al., 2015; Williams et al., 2015).

Subsurface drainage networks have two major effects. First, at the watershed scale, watersheds that were formerly dominated by high evapotranspiration (ET) rates, before the addition of subsurface drainage networks, have characteristically lower ET rates with the addition of drainage (Khand et al., 2017; Yang et al., 2017). Second, at the field scale, subsurface drainage networks act as additional hydrologic flow pathways, quickly transporting water and dissolved constituents to ditches and streams. As a consequence of the fast hydrologic flow paths indicative of these subsurface-drained landscapes, agricultural drainage has been indirectly connected to excessive nutrient transport to surface-water bodies (Hernandez-Ramirez et al., 2011; Ahiablame et al., 2011; King et al., 2014). These altered watersheds, some of the most productive agricultural lands in the world, have also become the focus of a large body of research because of the unintended consequences from...
agricultural runoff (Burkart and James, 1999; Jaynes et al., 1999; Klavdivko et al., 2004; Kanwar et al., 2005; Schilling et al., 2012; Smith et al., 2015).

One of the mechanisms that enables subsurface drainage efficiency is preferential flow (Heppell et al., 2002; Stone and Wilson, 2006; Fuchs et al., 2009; Nimmo, 2012; Williams et al., 2016). Preferential flow pathways bypass slower pathways dominated by matrix or diffuse flow processes (Jury and Horton, 2004). Because preferential flow has a shorter contact time with soils, this type of flow generally has less time for natural attenuation and thereby has a direct effect on nutrient and pesticide transport (Jørgensen et al., 2002). Macropores, a type of preferential flow pathway, form from plant root channels and the burrowing activity of earthworms and other animals (Heard et al., 1988; Jury and Horton, 2004). Macropore characteristics depend on soil type (Bouma, 1981), climate (Bergström et al., 2001), tillage management (Andreini and Steenhuis, 1990), and vegetation (Beven and Germann, 1982). Soil desiccation can also produce preferential flow pathways via cracks and fissures, especially in clay soils (Haria et al., 1994), and can vary seasonally because of soil drying variations (Oygarden et al., 1997; Stewart et al., 2016).

Rainfall intensity and soil antecedent moisture conditions affect the amount of preferential flow. Relative contributions to preferential flow (via macropores) increase after high-intensity storms on relatively dry soils (Edwards et al., 1993; Shipitalo and Edwards, 1996). However, preferential flow can also occur under ponded conditions when the entire pore space is fully saturated (Watson and Luxmoore, 1986). Despite these seemingly conflicting results, soil moisture conditions have been shown to have a strong effect on the resulting preferential flow. Differences found in the published literature among the amount of preferential flow under variable soil antecedent moisture conditions are probably influenced by the macropore characteristics, soil wetness, local topography, and soil organic matter (Germann and Beven, 1981; Sidle et al., 2000).

Aside from preferential flow, several hydrologic flow pathways exist in the water cycle for agricultural fields, including overland runoff, matrix flow, unsaturated zone flow, interflow, and groundwater flow. Water moving through different hydrologic flow paths has different characteristic time scales and degrees of interaction with the soil. These variable interactions yield different ionic contents because water increases in dissolved ionic concentrations with longer contact times (Pilgrim et al., 1979; Thomas and Phillips, 1979). An indirect measurement of ionic concentrations in water, specific conductance (SC), measures the ability of a water solution to conduct an electrical current. Because SC will increase with more dissolved ionic species in the water solution, SC can act as a characteristic tracer for the different hydrologic flow pathways. Water traveling through either more tortuous or slower flow paths will develop a higher SC value, while water traveling through preferential flow pathways will have a characteristically low SC. Using SC as a tracer of water contact time, the relative contribution of water via preferential flow can be calculated for specific storm events. In previous studies, high-frequency stream SC records have been shown to be useful watershed-scale tools to delineate relative source contributions on both short- and long-term time scales, noted as hours to a few days and several days to weeks, respectively (e.g., Heppell and Chapman, 2006; Schilling and Helmers, 2008; Kronholm and Capel, 2015).

In this research, we used a subsurface drain SC record to quantify the role that preferential flow plays in the timing and quantity of water moving through the shallow soil in an agricultural field with glacial till soils. The results demonstrate that significant preferential flow can occur even for low-intensity rainfall events. Also, changes in antecedent moisture conditions are not necessarily required for preferential flow, as we did not find a strong pattern in the correlation of the preferential flow speed or magnitude in relation to antecedent moisture conditions. Additionally, SC measurements from several hydrologic compartments (subsurface drain outlet, groundwater, overland runoff, rainfall, stream, unsaturated zone) were characterized as additional evidence of the utility of SC as a characteristic tracer of preferential flow. We developed methods to quantify changes in the timing and magnitude of the SC in the drain outlet, relative to rainfall, to provide insight into the movement of water through the shallow soil.

**Methods**

**Field Site and Sampling**

This study focused on a 38.8-ha row-cropped field within the upper portion of the South Fork Iowa River (SFIR) near the USGS stream gauge station (SFIR-Blairsburg; USGS station 05451080) (Fig. 1). The study site is located in Hamilton County, Iowa, approximately 7.6 km from the South Fork Iowa River headwaters, along the glacial margin of the Des Moines lobe (Prior, 1991). Two subsurface drains are in the study field, with outlets located just downstream from the stream gauge (Fig. 2). The installation date for the subsurface drains is unknown; additionally, the exact drainage configuration for the two drains is also unknown except for approximately the last 250 m confirmed by physical survey. For the portions beyond the physical survey, the drainage pattern was assumed to follow the natural slopes of the field. This study’s primary subsurface drain, TD1, terminated approximately 150 m southeast of the stream gauge. A second subsurface drain, TD2, terminated another 75 m further downstream from TD1.

Soils of the 38.8-ha field site, mainly of silt loam and silty clay loam textures, are developed on glaciogenic diamicton deposits (Quade et al., 2000). Along upland slopes, soils are predominantly the well-drained Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls). The poorly drained lowland soils are dominated by Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) and Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) loams (NRCS, 2004). Minor component soils also include the Harps (fine-loamy, mixed, superactive, mesic Typic Calciaquolls), Webster (fine-loamy, mixed, superactive, mesic Typic Endoaquolls), and Okoboji (fine,
smectitic, mesic Cumulic Vertic Endoaquolls) loams. Generally, the upper soil layer is 2 m in depth, with subsurface drainage generally lying approximately 1 to 1.5 m below the ground surface.

In addition to the primary field site, a second study location was used to characterize the SC signature for overland runoff. The second field site, an outlet culvert (SFIR-Overland; USGS station 42313509373301) that integrated overland runoff from a 228-ha drainage area, was located approximately halfway between the SFIR headwaters and the study site.

High-Frequency and Discrete Water Quality Data

Both subsurface drain outlets, TD1 and TD2, were outfitted with a specific conductivity and temperature probe (Campbell Scientific CS547A) attached to a datalogger that recorded instantaneous data every 15 min. High-frequency drainage discharge measurements, collected at the same frequency, were calculated for TD1 by using an area velocity module (Teledyne ISCO 2150) and converted to cubic meters per second based on Manning’s flow equation. The overland runoff site (SFIR-Overland), measured inside the outlet culvert to the stream, had the same equipment and collection frequency as the subsurface drain for the high-frequency SC, temperature, and discharge records. The SC for runoff events at the overland site was distinguished by periods with discernible discharge measurements.

Groundwater SC measurements were made from piezometer arrays, located <200 m from the stream gauge site in the study field (Fig. 2). The piezometers were divided into two categories: <2.8 m and >2.8 m below the land surface. The data are categorized by depth based on 2.8 m being the estimated maximum depth of surficial soils. All piezometers were bottom screened for 0.3 m. Piezometer samples were collected in July and October 2007 and April, June, and October 2008, with SC measurements made in conjunction with the collection of nutrient, alkalinity, and major ion samples. Due to the low hydraulic conductivities for the deep piezometers at this site (>2.8 m), deep piezometers were purged 2 wk prior to sampling and sampled without further purging at the sampling time. The SC was measured in the field, utilizing a YSI 6600 sonde. A total of 27 SC measurements were measured from 10 different <2.8-m piezometers; a total of 98 SC measurements were measured from 24 >2.8-m piezometers.

Unsaturated zone SC values were obtained from porous ceramic cup suction lysimeters (Soilmoisture Equipment Corp. Model 1920F1), installed at either 0.6 or 0.9 m below the ground surface, beneath the agricultural field close to the edge of the
grassy buffer strip (Fig. 2). To collect the samples, a 70-kPa suction was applied and water was collected for approximately 24 h. After 24 h, the withdrawn water’s specific conductance (SC) was then measured using the same procedure as for the groundwater samples. Unsaturated zone volumetric water content (VWC), cubic meters of water per cubic meter of soil, was obtained from soil moisture probes (Decagon EC-5) installed adjacent to the suction lysimeters (Fig. 2). The VWC measurements, VWC-0.6 and VWC-0.9, were from 0.6 and 0.9 m, respectively, below the land surface approximately 1 m away from TD1 (Fig. 2). Smith (2012) included more details on the VWC and the soil-specific calibration equation for the field site.

Other environmental data at the study site included 30-min precipitation data and discrete SC measurements from a temporary pond in the agricultural field. Precipitation, co-located at SFIR-Blairsburg, was measured with a 20.3-cm-diameter tipping bucket rain gauge (Texas Electronics TE525 WS). The SC measurements from the ponded water, surrounding a vertical inlet in a surface depression connected to TD2, were obtained from a series of temporary ponds during a 3-mo period between May and August 2008 (Roth, 2010; Roth and Capel, 2012). Precipitation SC data were obtained (via the website) from the National Atmospheric Deposition Program site at the Big Springs Fish Hatchery, located about 200 km northeast of the study area (USGS, 2011).

Paired Rainfall–Specific Conductance Events

Paired rainfall–SC events were classified for TD1 for the entire duration of the non-winter periods of 2007 and 2008: 20 Mar. 2007 to 5 Nov. 2008. A paired rainfall–SC event was classified as any SC decrease >10% of the previous 2-h SC average with a minimum total precipitation of 1.27 mm (0.05 inch). Also, an event was required to have at least a 2-h period of stable SC values prior to the initial decrease in SC to establish the mean pre-event SC value. The end of an SC event was determined when the SC of the drain water returned to 90% of the SC value preceding the event.

Several new parameters were derived from this analysis, including the following parameters for time, in minutes:

- \( \tau_S \): event start time of the first rainfall recorded at the tipping bucket for SC events, equal to 0 min
- \( \tau_{EO} \): event onset time from \( \tau_S \) to the initial decrease in the SC measurement
- \( \tau_{EM} \): event minimum time from \( \tau_S \) to the lowest SC measurement
- \( \tau_{50} \): time from \( \tau_S \) to 50% SC recovery, also known as 50% recovery
- \( \tau_{90} \): time from \( \tau_S \) to 90% SC recovery, also known as 90% recovery

Both \( \tau_{EO} \) and \( \tau_{EM} \) were in 15-min increments because this is the resolution of the SC record. Analogous SC parameters to the time parameters were also derived for each event, in microsiemens per centimeter:

- \( SC_{EO} \): mean SC value during a 2-h period preceding \( \tau_{EO} \)
- \( SC_{EM} \): SC value at \( \tau_{EM} \)
- \( SC_{50} \): SC value at \( \tau_{50} \)
- \( SC_{90} \): SC value at \( \tau_{90} \)

The \( SC_{50} \) and \( SC_{90} \) values were calculated with the following formulas, given that the time to 50 or 90% recovery often fell between two 15-min measurements. In turn, \( \tau_{EO} \) and \( \tau_{EM} \) were calculated based on the time between two consecutive SC measurements:

\[
SC_{50} = SC_{EM} + \left( \frac{(SC_{EO} - SC_{EM})}{0.50} \right)
\]

\[
SC_{90} = SC_{EM} + \left( \frac{(SC_{EO} - SC_{EM})}{0.90} \right)
\]

\[
\tau_{50} = \tau_{i-1} + \left[ \frac{15 (SC_{50} - SC_{i-1})}{SC_{i-1} - SC_i} \right]
\]

\[
\tau_{90} = \tau_{i-1} + \left[ \frac{15 (SC_{90} - SC_{i-1})}{SC_{i-1} - SC_i} \right]
\]

Figure 3 shows a sample event, with the time and SC parameters illustrated, after a 25.7-mm rainfall on 6 May 2007 (Fig. 3). Within 105 min (\( \tau_{EO} \)) from the initial rainfall, the initial SC decrease occurred and reached the event minimum, \( \tau_{EM} \), in
195 min. Recovery to $SC_{50}$ and $SC_{90}$ occurred at $t_{50} = 287$ min and $t_{90} = 428$ min, respectively.

As part of the quality assurance for the high-frequency SC data, the subsurface drain SC data were censored when: (i) the stream gauge height was above 1.92 m (avoiding periods when the SFIR submerged the subsurface drain outlet), (ii) when the SC probe in the subsurface drain was not completely submerged due to low drain flow, (iii) during random, short-duration SC spikes $>50 \mu S/cm$ over the previous 2-hr SC moving average (presumably due to random spike effects unrelated to precipitation).

### Specific Conductance End-Member Mixing Analysis Model

A mass-balance mixing model for TD1 used two sources with direct input into the subsurface drain: fast flow and slow flow. Fast flow consisted of preferential flow, whereas slow flow considered soil matrix flow and groundwater inputs when the subsurface drain was below the locally perched water table. Subsurface drain discharge, fast flow, and slow flow were represented by $Q_{DF}$, $Q_{FF}$, and $Q_{SF}$, respectively. Subsurface drain SC, fast flow SC, and slow flow SC were represented by $SC_{DF}$, $SC_{FF}$, and $SC_{SF}$, respectively. For the mass balance, the $SC_{SF}$ value was equal to $SC_{EO}$, assuming that prior to an event all the flow was derived from slow flow sources rather than preferential flow sources. The basic mass balance was determined as

$$Q_{DF}SC_{DF} = Q_{FF}SC_{FF} + Q_{SF}SC_{SF}$$  \[5\]

$$Q_{DF} = Q_{FF} + Q_{SF}$$  \[6\]

The relative amounts of slow and fast flow were calculated during periods of known subsurface drain SC and discharge by combining Eq. [5] and [6]:

$$Q_{FF} = \frac{Q_{DF}SC_{DF} - Q_{DF}SC_{SF}}{SC_{FF} - SC_{SF}}$$  \[7\]

A value of 12 $\mu S/cm$, based on the mean precipitation SC at the Big Springs Fish Hatchery (USGS, 2011), was used for the low-SC water ($SC_{FF}$; Table 1). In combination with a substitution of $SC_{EO}$ for $SC_{SF}$, assuming that all subsurface drain discharge ($Q_{DF}$) prior to the event was from slow flow sources ($Q_{SF}$), the amount of fast flow ($Q_{FP}$, low-SC water) was calculated.

An end-member mixing analysis (EMMA) based on two end members ($Q_{FF}$ and $Q_{SF}$) was used to determine the volume of water that infiltrated through preferential flow pathways (fast flow water). This volume, combined with the ongoing subsurface drain flow, resulted in decreased SC ($SC_{EM}$) in the subsurface drain water ($SC_{DF}$) during and directly after rain events. To develop the EMMA relation in Eq. [7] and [8], two assumptions were necessary. First, the mean SC value for precipitation was used for fast flow sources based on the mean from the 2-yr record (Table 1). Second, the fast flow was due to preferential flow.

### Results and Discussion

**Specific Conductance for Hydrologic Flow Pathways**

The sources of water for the study site can be grouped into three distinct categories (Table 1): hydrologic flow pathways with low-SC water (i.e., short contact time), hydrologic flow pathways with intermediate-SC water (i.e., intermediate contact time), and hydrologic flow pathways with high-SC water (i.e., longest contact time). Low-SC water included precipitation, overland runoff, and the water in the temporary ponds. Only water <5 h from the overland runoff site was included because that was approximately the mean time of the classified rainfall–SC events.

A major observation from the 2-yr study was the fast decrease in SC after relatively small rainfall events during the course of
25 paired rainfall–SC events (Table 2). Specific conductance decreased within 101 min on average ($t_{EO}$) after initial rainfall and reached an event minimum shortly thereafter, 141 min on average ($t_{EM}$). The difference between the mean $SC_{EO}$ and $SC_{EM}$ (188 µS/cm) represented a 29% decrease in SC. This indicated a substantial water source not equilibrated with the surrounding soil matrix, characteristic of new rainwater infiltrating from the land surface via preferential flow (e.g., macropores). Most SC events were also short lived without sustained periods of depressed SC values, as indicated by the $t_{50}$ and $t_{90}$, which had mean values of 209 and 288 min, respectively.

### Specific Conductance End-Member Mixing Analysis Results

Several researchers have used continuous SC to conduct an EMMA of stream discharge, including Laudon and Slaymaker (1997), Kobayashi (1986), and Arenas Amado et al. (2017). Schilling and Helmers (2008) used discrete SC measurements of subsurface drain discharge to separate conduit and diffuse flow, analogous to preferential and matrix flow. For this study, EMMA was used on the continuous subsurface drain flow record for 20 of the 25 paired rainfall–SC events classified from TD1 (Table 3). Of the 20 classified events, the maximum preferential flow ranged from 11 to 75% of the total subsurface drain flow, with a mean maximum preferential flow of 31%.

Preferential flow seasonality could not be distinguished with the SC-EMMA. No subsurface drain flow record was available from 14 May to 15 Nov. 2007; therefore, SC-EMMA could not be conducted on the other five paired rainfall–SC events that fell within this 6-mo period. Only 2008 had a complete record during the frost-free period. Furthermore, several paired rainfall–SC events from 2008 could not be used because the events fell within censored periods when the SFIR submerged the subsurface drain outlet.

### Preferential Flow Mechanisms

These results clearly show that preferential flow reaches the subsurface drain consistently after small rainfall events, often <5 mm (0.20 inch), with maximum preferential flow up to 75%. Previous studies have focused on larger rainfall events as the primary cause of preferential flow events (Zhao et al., 2001; Vidon and Cuadra, 2011), while our study demonstrates

---

**Table 1. Summary of the characteristic specific conductance (SC) of the various sources of water to the stream. The different environmental compartments are sorted from lowest to highest mean SC value.**

<table>
<thead>
<tr>
<th>Environmental compartment</th>
<th>Number of stations</th>
<th>Total observations</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>5th percentile</th>
<th>95th percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrologic compartments with intermediate SC water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation†</td>
<td>1</td>
<td>86</td>
<td>12</td>
<td>11</td>
<td>6</td>
<td>4</td>
<td>23</td>
</tr>
<tr>
<td>Overland runoff, &lt;5 h</td>
<td>1</td>
<td>160</td>
<td>70</td>
<td>65</td>
<td>41</td>
<td>22</td>
<td>143</td>
</tr>
<tr>
<td>Temporary pond‡</td>
<td>1</td>
<td>15</td>
<td>129</td>
<td>136</td>
<td>64</td>
<td>43</td>
<td>254</td>
</tr>
<tr>
<td>Unsaturated zone</td>
<td>6</td>
<td>10</td>
<td>456</td>
<td>461</td>
<td>173</td>
<td>63</td>
<td>702</td>
</tr>
<tr>
<td>Subsurface drain</td>
<td>1</td>
<td>49,330</td>
<td>654</td>
<td>690</td>
<td>122</td>
<td>387</td>
<td>795</td>
</tr>
<tr>
<td>Groundwater, &lt;2.8 m</td>
<td>10</td>
<td>27</td>
<td>675</td>
<td>654</td>
<td>120</td>
<td>512</td>
<td>894</td>
</tr>
<tr>
<td>Stream§</td>
<td>1</td>
<td>37,856</td>
<td>681</td>
<td>715</td>
<td>105</td>
<td>470</td>
<td>809</td>
</tr>
<tr>
<td>Groundwater, &gt;2.8 m</td>
<td>24</td>
<td>98</td>
<td>863</td>
<td>829</td>
<td>156</td>
<td>636</td>
<td>1118</td>
</tr>
</tbody>
</table>

† Weekly integrated samples from Big Springs Fish Hatchery (NADP IA08) (USGS, 2011).
‡ Grab samples from a series of temporary ponds during a 3-mo period between May and August 2008 (Roth, 2010).
§ Average of all measurements at the South Fork Iowa River at Blairsburg (USGS 03451080).

**Table 2. Summary of the calculated time ($t$) and specific conductance (SC) parameters for the 25 paired rainfall–SC events. All the parameters are relative to the beginning time of an event ($t_S$).**

<table>
<thead>
<tr>
<th>Parameter†</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{EO}$</td>
<td>101</td>
<td>90</td>
<td>50</td>
<td>15</td>
<td>240</td>
</tr>
<tr>
<td>$t_{EM}$</td>
<td>141</td>
<td>135</td>
<td>65</td>
<td>60</td>
<td>300</td>
</tr>
<tr>
<td>$t_{50}$</td>
<td>209</td>
<td>192</td>
<td>105</td>
<td>88</td>
<td>509</td>
</tr>
<tr>
<td>$t_{90}$</td>
<td>288</td>
<td>273</td>
<td>121</td>
<td>141</td>
<td>572</td>
</tr>
<tr>
<td>$SC_{EO}$</td>
<td>654</td>
<td>652</td>
<td>37</td>
<td>593</td>
<td>754</td>
</tr>
<tr>
<td>$SC_{EM}$</td>
<td>466</td>
<td>496</td>
<td>107</td>
<td>165</td>
<td>595</td>
</tr>
<tr>
<td>$SC_{50}$</td>
<td>560</td>
<td>573</td>
<td>61</td>
<td>399</td>
<td>664</td>
</tr>
<tr>
<td>$SC_{90}$</td>
<td>635</td>
<td>637</td>
<td>38</td>
<td>569</td>
<td>735</td>
</tr>
</tbody>
</table>

† $t_{EO}$: event onset time; $t_{EM}$: event minimum; $t_{50}$: 50% SC recovery back to pre-event SC; $t_{90}$: 90% SC recovery back to pre-event SC; $SC_{EO}$: mean SC value during a 2-h period preceding $t_{EO}$; $SC_{EM}$: SC value at $t_{EM}$; $SC_{50}$: SC value at $t_{50}$; $SC_{90}$: SC value at $t_{90}$.
that preferential flow happens in response to even small rainfall events. Additionally, other mechanisms used to explain the presence or absence of preferential flow in other studies have included antecedent moisture conditions (Kung et al., 2000), storm rainfall intensity (Vidon and Cuadra, 2011), crop growth and evapotranspiration (Kumar et al., 1997), surface ponding when the entire pore space is fully saturated (Watson and Luxmoore, 1986), and the swelling of saturated, clay-rich soils (Leeds-Harrison et al., 1986).

Based on our findings, there are two primary preferential flow mechanisms that can be demonstrated. One of these, fast increases in soil moisture, occasionally produced preferential flow. However, most of the preferential flow events from these relatively small rainfall events can be explained by open macropores or preferential flow pathways via cracks and fissures that quickly route new rainfall to the subsurface drain. In these cases, shifts in soil moisture do not explain the sudden decreases in the subsurface drain SC or increases in the subsurface drain flow.

### Soil Moisture and Preferential Flow

The high-frequency VWC measurements for the 2007 to 2008 period show that the VWC shifted >1% in only 4 of the 25 paired rainfall–SC events, or 16% of the events discussed here (Table 3). Furthermore, these four events are not necessarily the largest events presented here, and there is no seasonal component evident although this is a very small sample. A larger population of rainfall–SC events in the censored data set did show more preferential flow events associated with soil moisture shifts, but at a similar ratio of 22%.

Figure 4 presents the SC-EMMA for three of the four classified events associated with large VWC shifts, broken into three panels showing events from 22 Apr. and 7 May 2007 in the upper

---

**Table 3. Summary of the individual paired rainfall–specific conductance (SC) events (25), including total precipitation (ppt), the event high volumetric water content at the 0.6-m depth (VWC-0.6), event maximum preferential flow (Q_FF), and all calculated time (t) and SC parameters. All the parameters are relative to the beginning time of an event (t EO = event onset time, t EM = event minimum, t 50 = 50% SC recovery back to pre-event SC, t 90 = 90% SC recovery back to pre-event SC, SC EO = mean SC value during a 2-h period preceding t EO, SC EM = SC value at t EM, SC 50 = SC value at t 50).**

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Time</th>
<th>Total ppt</th>
<th>VWC-0.6</th>
<th>Q_FF</th>
<th>SC EO</th>
<th>SC EM</th>
<th>SC 50</th>
<th>SC 90</th>
<th>t EO</th>
<th>t EM</th>
<th>t 50</th>
<th>t 90</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29 Mar. 2007</td>
<td>22:00</td>
<td>2.5</td>
<td>0.29</td>
<td>0.17</td>
<td>662</td>
<td>554</td>
<td>608</td>
<td>651</td>
<td>75</td>
<td>75</td>
<td>125</td>
<td>183</td>
</tr>
<tr>
<td>2</td>
<td>30 Mar. 2007</td>
<td>03:30</td>
<td>1.8</td>
<td>0.29</td>
<td>0.26</td>
<td>668</td>
<td>498</td>
<td>583</td>
<td>651</td>
<td>45</td>
<td>60</td>
<td>88</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>14 May 2007</td>
<td>01:00</td>
<td>3.6</td>
<td>0.29</td>
<td>0.15</td>
<td>667</td>
<td>569</td>
<td>618</td>
<td>657</td>
<td>105</td>
<td>210</td>
<td>240</td>
<td>287</td>
</tr>
<tr>
<td>4</td>
<td>31 Mar. 2007</td>
<td>02:00</td>
<td>9.4</td>
<td>0.30</td>
<td>0.45</td>
<td>668</td>
<td>372</td>
<td>520</td>
<td>639</td>
<td>45</td>
<td>135</td>
<td>164</td>
<td>283</td>
</tr>
<tr>
<td>5</td>
<td>07:30</td>
<td>5.1</td>
<td>0.30</td>
<td>0.24</td>
<td>638</td>
<td>486</td>
<td>562</td>
<td>622</td>
<td>60</td>
<td>105</td>
<td>153</td>
<td>255</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>22 Apr. 2007</td>
<td>12:30</td>
<td>8.1</td>
<td>0.31</td>
<td>0.34</td>
<td>655</td>
<td>439</td>
<td>547</td>
<td>633</td>
<td>105</td>
<td>135</td>
<td>192</td>
<td>N/A†</td>
</tr>
<tr>
<td>7</td>
<td>17:00</td>
<td>7.6</td>
<td>0.44</td>
<td>0.48</td>
<td>615</td>
<td>325</td>
<td>473</td>
<td>590</td>
<td>60</td>
<td>90</td>
<td>128</td>
<td>161</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6 May 2007</td>
<td>04:00</td>
<td>25.7</td>
<td>0.43</td>
<td>0.41</td>
<td>593</td>
<td>355</td>
<td>474</td>
<td>569</td>
<td>105</td>
<td>195</td>
<td>287</td>
<td>428</td>
</tr>
<tr>
<td>9</td>
<td>14 May 2007</td>
<td>18:00</td>
<td>2.8</td>
<td>0.42</td>
<td>N.R.</td>
<td>617</td>
<td>529</td>
<td>573</td>
<td>608</td>
<td>75</td>
<td>90</td>
<td>113</td>
<td>141</td>
</tr>
<tr>
<td>10</td>
<td>21 June 2007</td>
<td>16:00</td>
<td>2.8</td>
<td>0.34</td>
<td>N.R.</td>
<td>638</td>
<td>552</td>
<td>595</td>
<td>629</td>
<td>90</td>
<td>90</td>
<td>133</td>
<td>171</td>
</tr>
<tr>
<td>11</td>
<td>22 June 2007</td>
<td>02:30</td>
<td>12.7</td>
<td>0.51</td>
<td>N.R.</td>
<td>640</td>
<td>303</td>
<td>471</td>
<td>606</td>
<td>90</td>
<td>120</td>
<td>509</td>
<td>705</td>
</tr>
<tr>
<td>12</td>
<td>9 July 2007</td>
<td>02:00</td>
<td>1.8</td>
<td>0.35</td>
<td>N.R.</td>
<td>628</td>
<td>563</td>
<td>595</td>
<td>622</td>
<td>135</td>
<td>150</td>
<td>230</td>
<td>422</td>
</tr>
<tr>
<td>13</td>
<td>5 Oct. 2007</td>
<td>08:30</td>
<td>3.8</td>
<td>0.35</td>
<td>N.R.</td>
<td>732</td>
<td>595</td>
<td>664</td>
<td>719</td>
<td>165</td>
<td>195</td>
<td>245</td>
<td>316</td>
</tr>
<tr>
<td>14</td>
<td>10 Apr. 2008</td>
<td>09:00</td>
<td>5.6</td>
<td>0.33</td>
<td>0.25</td>
<td>754</td>
<td>570</td>
<td>662</td>
<td>735</td>
<td>195</td>
<td>270</td>
<td>396</td>
<td>N/A†</td>
</tr>
<tr>
<td>15</td>
<td>15:30</td>
<td>6.6</td>
<td>0.44</td>
<td>0.32</td>
<td>662</td>
<td>453</td>
<td>558</td>
<td>641</td>
<td>90</td>
<td>180</td>
<td>209</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>17 Apr. 2008</td>
<td>08:30</td>
<td>2.3</td>
<td>0.33</td>
<td>0.13</td>
<td>656</td>
<td>570</td>
<td>613</td>
<td>647</td>
<td>120</td>
<td>130</td>
<td>176</td>
<td>212</td>
</tr>
<tr>
<td>17</td>
<td>18 Apr. 2008</td>
<td>10:30</td>
<td>7.6</td>
<td>0.34</td>
<td>0.40</td>
<td>658</td>
<td>401</td>
<td>530</td>
<td>633</td>
<td>90</td>
<td>195</td>
<td>233</td>
<td>333</td>
</tr>
<tr>
<td>18</td>
<td>22 Apr. 2008</td>
<td>02:30</td>
<td>4.8</td>
<td>0.34</td>
<td>0.24</td>
<td>652</td>
<td>496</td>
<td>574</td>
<td>637</td>
<td>75</td>
<td>75</td>
<td>118</td>
<td>186</td>
</tr>
<tr>
<td>19</td>
<td>23 May 2008</td>
<td>06:00</td>
<td>7.6</td>
<td>0.35</td>
<td>0.29</td>
<td>622</td>
<td>442</td>
<td>532</td>
<td>604</td>
<td>60</td>
<td>75</td>
<td>145</td>
<td>201</td>
</tr>
<tr>
<td>20</td>
<td>27 June 2008</td>
<td>17:00</td>
<td>9.1</td>
<td>0.42</td>
<td>0.75</td>
<td>634</td>
<td>165</td>
<td>399</td>
<td>587</td>
<td>15</td>
<td>60</td>
<td>102</td>
<td>441</td>
</tr>
<tr>
<td>21</td>
<td>6 July 2008</td>
<td>18:30</td>
<td>1.8</td>
<td>0.40</td>
<td>0.11</td>
<td>651</td>
<td>580</td>
<td>615</td>
<td>644</td>
<td>135</td>
<td>150</td>
<td>224</td>
<td>324</td>
</tr>
<tr>
<td>22</td>
<td>9 July 2008</td>
<td>14:30</td>
<td>3.8</td>
<td>0.40</td>
<td>0.22</td>
<td>652</td>
<td>513</td>
<td>583</td>
<td>638</td>
<td>90</td>
<td>90</td>
<td>140</td>
<td>198</td>
</tr>
<tr>
<td>23</td>
<td>21 July 2008</td>
<td>01:30</td>
<td>11.9</td>
<td>0.44</td>
<td>0.21</td>
<td>595</td>
<td>470</td>
<td>533</td>
<td>582</td>
<td>105</td>
<td>150</td>
<td>219</td>
<td>264</td>
</tr>
<tr>
<td>24</td>
<td>24 July 2008</td>
<td>05:30</td>
<td>4.3</td>
<td>0.40</td>
<td>0.26</td>
<td>667</td>
<td>499</td>
<td>583</td>
<td>651</td>
<td>165</td>
<td>210</td>
<td>224</td>
<td>303</td>
</tr>
<tr>
<td>25</td>
<td>12 Aug. 2008</td>
<td>07:00</td>
<td>4.6</td>
<td>0.36</td>
<td>0.51</td>
<td>714</td>
<td>353</td>
<td>533</td>
<td>678</td>
<td>240</td>
<td>300</td>
<td>437</td>
<td>572</td>
</tr>
</tbody>
</table>

† N/A, not available.
Fig. 4. Precipitation, subsurface drain specific conductance (SC), total subsurface drain discharge, and calculated preferential flow for rainfall–SC events from subsurface drain TD1 and volumetric water content from the 0.6-m depth approximately 1 m away from TD1 (VWC-0.6): (A) 22 Apr. 2007; (B) 6 May 2007; and (C) 10 Apr. 2008.
two panels and 10 to 11 Apr. 2008 in the bottom panel. In all three events, the VWC record increased after rainfall initiated and returned close to the pre-event baseline VWC within a 3- to 5-h window. However, the VWC shift in relation to the preferential flow discharge does not necessarily coincide.

For the rain event on 22 Apr. 2007 (Fig. 4A), the first SC decrease occurred after 8.1 mm of rainfall (Table 3, Event 6), with a \( \tau_{EO} \) of 105 min and \( \tau_{EM} \) after 135 min. There was no VWC shift during the first event, although 34% of the total subsurface drain flow was attributed to preferential flow. Hours later, a second rainfall event of 7.6 mm (Table 3, Event 7) caused a sharp VWC increase from 31 to 44%. The \( Q_{FF} \) peak quickly followed within approximately 1 h of the VWC rise, although the maximum preferential flow (\( Q_{FF} \)) of 48% occurred as the VWC percentage was dropping back toward the pre-event VWC baseline. This VWC increase probably demonstrates the preferential flow passing within the vicinity of the soil moisture probe before reaching the subsurface drain.

For the rain event on 7 May 2007 (Fig. 4B), 25.7 mm of rainfall occurred during a 7-h period, with the event onset (\( \tau_{EO} \)) occurring after 195 min (Table 3, Event 8). The \( Q_{FF} \) percentage peaked at 41% of the total discharge after only 90 min from the \( \tau_{EO} \), or 195 min from \( t_s \). After 4.5 h from the beginning of the event, only <10% of the flow was attributed to \( Q_{FF} \). In this case, the VWC increased after the peak preferential flow, with a lag of approximately 90 min between the peak preferential flow and the peak VWC.

Finally, the rain event on 10 Apr. 2008 (Fig. 4C) shows two paired rainfall–SC events, although several dips in the SC record occurred causing varying amounts of preferential flow. The two events had maximum \( Q_{FF} \) values of 25 and 32%, respectively, with the larger preferential flow event between 18:00 and 19:00 h coinciding with an increase in VWC from 33 to 44%. As with the other two events, the VWC approached the pre-event VWC baseline as the preferential flow event ended.

Overall, these examples demonstrate that a straightforward relation between high antecedent moisture conditions and the timing of preferential flow does not exist for these soils. Because only four paired rainfall–SC events had appreciable VWC shifts, the primary mechanism for preferential flow initiation at our site cannot be explained by soil moisture near or at saturation.

However, a clear pattern does emerge if these paired rainfall–SC events with high antecedent moisture conditions, plus all other events with an initial VWC >35%, are eliminated from the full set of 25 paired rainfall–SC events. Fourteen of the 25 paired rainfall–SC events had VWC \( \leq 35\% \). If the total precipitation from these events (Table 3) is plotted against the ratio (\( SC_{EO} - SC_{EM} \))/\( SC_{EO} \), a surrogate for defining the size of a specific conductance (SC) event using SC values for the event onset (EO) and event minimum (EM), for 14 rainfall–SC events with event volumetric water content (VWC) values at or below 35%. The coefficient of determination (\( R^2 \)) for this relation was 0.79.

### Preferential Flow through Macropores

Twenty-one of the 25 paired rainfall–SC events cannot be explained by antecedent moisture condition shifts. Therefore, the mechanism must be related to either open macropore flow or preferential flow pathways via cracks and fissures. Storm rainfall intensity and overall total rainfall as mechanisms for initiating preferential flow can be eliminated because of the nature of the events used in this study, although total rainfall has been shown to explain the size of the event (Fig. 5). The relatively small size of the paired rainfall–SC events also eliminated surface ponding as a major mechanism; the mean total porosity for these soils was 47.1%, and most events occurred well below this threshold (Table 3).

Figure 6 presents the SC-EMMA for 12 paired rainfall–SC events, broken into eight different panels (Fig. 6A–6H), that demonstrate either open macropore flow or preferential flow pathways through cracks or fissures. These events are illustrative examples of this type of preferential flow, although the other events not shown in Table 3 unrelated to VWC shifts can be explained by open macropore flow.

Figure 6A shows a series of five different events (Table 3, Events 1–5) between 29 and 31 Mar. 2007, occurring early in the year before any spring tillage would have disturbed established macropores. The maximum \( Q_{FF} \) ranged from 15 to 45% of the total subsurface drain flow. The start of the SC event (\( \tau_{EO} \)) for the five events ranged between 45 and 105 min after rainfall initiated, and \( \tau_{EM} \) ranged from 75 to 210 min. All five of these events rebounded quickly to \( \tau_{90} \) between 183 and 287 min. The
Fig. 6. Precipitation, subsurface drain specific conductance (SC), total subsurface drain discharge, and calculated preferential flow for rainfall–SC events from subsurface drain TD1: (A) 29–31 Mar. 2007; (B) 18 Apr. 2008; (C) 22 Apr. 2008; (D) 23 May 2008; (E) 27–28 June 2008; (F) 9 July 2008; (G) 21 July 2008; and (H) 12 Aug. 2008.
12 Apr. 2008, which would have potentially disrupted established VWC during this period remained relatively constant between 29 and 30%.

Figures 6B to 6D also show a similar response as Fig. 6A, with a modest rainfall event preceded by a drop in subsurface drain SC that is evidence of preferential flow passing to the drain. Also, similar to Fig. 6A, Fig. 6B to 6D (Table 3, Events 17–19) ranged from 24 to 40% of total subsurface drain flow. Total rainfall for these events ranged from 4.8 to 7.6 mm, with $t_{EO}$ ranging from 75 to 120 min and $t_{EM}$ from 75 to 195 min. However, although it is subtle, these events did seem to exhibit a more subdued and slightly drawn out preferential flow initiation and dissipation compared with the Fig. 6A events. While macropores are still the probable explanation, these events occurred after spring tillage occurred on 12 Apr. 2008, which would have potentially disrupted established large macropores connected to the land surface, leading to the less succinct nature of the preferential flow event.

Figures 5E to 5H occurred during a period of high evapotranspiration and crop growth. These events also occurred during a period when preferential flow pathways caused by cracks and fissures were another probable mechanism; Fig. 7 shows visible cracking from near Piezometer Nest A (Fig. 2) on 29 June 2008. Figure 6E (Table 3, Event 20) shows the highest $Q_{FF}$ throughout the 2-yr period, with 75% of the total subsurface drain flow attributed to preferential flow. This was coincident with 9.1 mm of rainfall, with a $SC_{EM}$ of 165 $\mu$S/cm after only 60 min ($t_{EM}$).

The SC returned toward pre-event values after only 102 min ($t_{EO}$), although this event did have a long tail. Figures 5F to 5G (Table 3, Events 22–23) show modest SC events caused by increased preferential flow, although these July events clearly illustrate that preferential flow does not seem to be as important in both the size of the event and the overall $Q_{FF}$. This is probably because the higher ET rates used more of the incoming water, leading to a relatively smaller preferential flow event. Finally, Fig. 6H (Table 3, Event 25) shows one last event in the 2-yr period with a large decrease in SC caused by a high relative amount of preferential flow (51%), although the overall subsurface drain flow during this period was 0.001 m$^3$/s.

Overall, SC-EMMA has shown that a significant portion of the subsurface drain discharge can be attributed to preferential flow, mainly through macropores or other largely open preferential flow pathways. The findings in this study are in line with the findings of Shipitalo and Edwards (1996), who found that some of the highest macropore flow occurred even under drier soil conditions, although our study demonstrates this phenomenon for smaller events. It is important to note that this goes against the conventional understanding of unsaturated zone flow and the framework for certain models such as RZWQM (Ahuja et al., 1993), with macropore flow starting only after all the smaller pores are saturated and surface ponding begins to occur (Watson and Luxmoore, 1986). However, as noted by Nimmo (2010), the unsaturated zone is often not in equilibrium between the smaller and larger pores, leading to infiltration through larger pores (i.e., macropores) even under less saturated conditions.

This SC-EMMA technique can only be used as a tracer of preferential flow during the early stages after a rainfall event, as the precipitation water passing through the soil matrix will begin to equilibrate. Preferential flow is probably an important flow pathway beyond our simple method’s detection limits in the early stages, further underestimating the amount of preferential flow that occurs.

### Conclusions

In agricultural areas with soils developed on glacial deposits, the presence of artificial surface and subsurface drainage networks provides additional pathways of water movement to the stream. In this study, preferential flow was shown to be an important water pathway from the land surface to the subsurface drain, connecting the land surface directly to the stream via the subsurface drain. The purpose of this study was to use a high-frequency SC record to determine the temporal pattern of preferential flow contribution to the overall subsurface drainage discharge during and after rainfall events and to characterize the SC signature for different types of water sources and flow pathways. Specific conductance and discharge were monitored inside a subsurface agricultural drain to differentiate the preferential flow paths from slow flow paths. Additionally, VWC was collected to characterize the soil moisture conditions to interpret the potential role of antecedent moisture conditions to preferential flow timing and magnitude.

A major observation from the 2-yr study was the fast decrease in SC after relatively small rainfall events during the course of 25 paired rainfall–SC events. These results clearly show that preferential flow reaches the subsurface drain consistently after small rainfall events, often <5 mm (0.20 inch). Previous studies have focused on larger rainfall events as the primary cause of preferential flow events, while our study demonstrates that preferential flow happens in response to even small rainfall events. The SC decreased within 101 min on average after initial rainfall. The difference in the mean SC at the onset of a paired rainfall–SC event and the event minimum was 188 $\mu$S/cm, representing a
29% decrease in SC. This indicated a substantial water source not equilibrated with the surrounding soil matrix, characteristic of new rainwater infiltrating from the land surface via preferential flow (e.g., macropores).

Most SC events were also short lived, without sustained periods of depressed SC values, as indicated by the $\tau_{50}$ and $\tau_{90}$, which had mean values of 209 and 288 min, respectively. These parameters, along with $\tau_{EO}$ (event onset time) and $\tau_{EM}$ (event minimum time), were used as an indication of the length of a paired rainfall–SC event and to compare different events. The subsurface drain SC generally returned to the typical base-flow values during the following hours, demonstrating a short travel distance and relatively fast hydrologic flow path.

An SC-EMMA based on two end members ($Q_{EF}$ and $Q_{SF}$) was used to determine the volume of water that infiltrated through preferential flow pathways (fast flow water). This methodology provided quantitative evidence of substantial macropore flow from early spring to midsummer. The SC-EMMA was used for 20 of the 25 paired rainfall–SC events classified from TD1, the main subsurface drain of this study. Of the 20 classified events, the maximum preferential flow ranged from 11 to 75% of the total subsurface drain flow, with a mean maximum preferential flow of 31%. Overall, SC-EMMA illustrated that a significant portion of the subsurface drain discharge can be attributed to preferential flow, mainly through macropores or other largely open preferential flow pathways.

Only 4 of the 25 paired rainfall–SC events could be explained by antecedent moisture conditions shifts, where VWC shifted >1% during the rainfall–SC event. However, if the events with large VWC shifts were not considered along with all events with VWC $\geq$ 35%, the relation between cumulative rainfall and the ratio ($SC_{EO} - SC_{EM}$)/$SC_{EO}$, a surrogate for defining the size of an SC event, had an $R^2$ of 0.79. Because the soils at the study site were generally >25% during the 2-yr period, preferential flow seemed to definably occur in the range between 25 and 35% in relation to the amount of rainfall; in these cases, the smaller pores are saturated such that the suction from smaller pores would not absorb infiltrating water, but the larger macropores remained open for infiltrating water.

Specific conductance as a tracer of preferential flow was shown to be an effective tool for deciphering the contribution of preferential flow to subsurface drains. Even during relatively dry periods, the SC had a substantial decrease shortly after a rainfall event, contrary to the conventional idea that macropore flow starts only after all the smaller pores are saturated and surface ponding begins to occur. The relation between the antecedent moisture conditions and preferential flow was relatively weak, leading to the more likely mechanism of open macropores or preferential flow pathways such as cracks and fissures. These fast flow pathways can be an important delivery mechanism for dissolved nutrients, pesticides, and other agriculture-related chemicals because the short delivery time to subsurface drains would not allow for a high degree of attenuation.

Acknowledgments
This study was conducted as part of the USGS National Water Quality Assessment Program and benefited from the work of many individuals involved in planning and execution. We thank Stephen Kalkhoff and Richard Johnson for helpful comments and suggestions for improving the original manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

References