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TECHNICAL ARTICLES

# INFILTRATION AND MACROPOROSITY UNDER A ROW CROP AGRICULTURAL FIELD IN A GLACIAL TILL SOIL[1]

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**Previous field-scale infiltration studies showed difference in the magnitude and the trend of spatial variation of infiltration rates under different soil water tensions. In different studies the differences in infiltration rates are caused by management practices, relative field positions, and soil and topographic setups, hence warranting further site-specific infiltration studies. In this study, variability in infiltration rate (Iv) at four soil water pressure heads, ψ, were investigated in a no-tillage agricultural field under corn rows, nontrafficked interrows, and traflicked interrows in a central Iowan glacial till soil. Automated disc infiltrometers were used to measure infiltration at 0-, 30-, 60-, and 150-mm tensions at 296 sites arranged on two parallel transects perpendicular to corn rows. Mean infiltration rates at different soil water tensions were found maximum under corn row, minimum for trafficked interrow, and intermediate for nontrafficked interrow positions. Maximum variability was found for larger pores (those conducing water at O-mm tension) under all three surface positions (corn row, CV = 85%; trafficked interrow, CV = 95%; nontrafficked interrow, CV = 124%). Infiltration at saturation (O-mm tension) showed a different scale of heterogeneity than infiltration at other (30-, 60-, and 150~mm) tensions, and approximately 90% of the saturated flux moves through macropores (>l-mm diameter) that constitute less than 3% of the total surface area at three field positions. Spatial analysis of Iv indicated a larger proportion of random variations under all three field positions in the glacial till soil. In addition to the large random noise, a small spatial structure of 7.6 to 11.4-m range was found for Iv (at all four tensions) under corn row position, and only for $I_{150}$ under (nontrafficked and trafficked) interrow positions.**

INFILTRATION of water into soil is controlled by a complex set of soil physical and biotic factors. Soil types (texture, structure, depositional pattern, etc.), environmental set up (forested watershed, agricultural watershed, hill slope, well drained topography, etc.), relative field positions (crop row, trafficked interrow, nontrafficked interrow, etc.), and tillage practices (conventional till, no-till, ridge till, etc.) are some of the factors that impact soil water infiltration rate and its variability, Glacial deposits constitute one of the most complex and variable materials on the earth's surface. Pleistocene ice sheets that advanced and retreated several times over central North America covered regions that in preglacial times were topographically low and exhibited little relief. Preglacial landscapes usually consist of low, rolling hills and well integrated, large-sized drainage systems, underlain by only moderately resistant rocks.The landforms and landscapes found in the central lowland areas of glacial deposits are chiefly morainal. Swell and swale topography dominates

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in the-areas of ground moraine (Boone, IA). Here, drainage is poorly developed, and relief is usually so low that the unevenness of the land surface is barely noticeable to the eye. Undrained depressions hold swamps or shallow lakes. Surface infiltration and the field-scale variability of this complex natural topographical setup of glacial till material further manipulated by agricultural practices is of interest to soil scientists and engineers to address non-point source pollution problems.

Ankeny et al. (1990),Zuzel et al. (1990), Starr (1990). Meek et al. (1989, 1992), and Dunn and Philips (1991) reported the effects of tillage, traffic, and fertilizer on infiltrarion rate.Ankeny et al. (1990) found little effect of tillage and a large effect of traffic on infiltration rates on aTama soil in Iowa. Dunn and Phillips (1990), however, found the effect of tillage on infiltration rates in a Maury silt loam soil in Kentucky Moreover, differences in the ranges and trends of coefficient of variation (CV) of infiltration rates at different soil water pressures were encountered by different researchers under different environmental conditions. For example. Watson and Luxmoore (1986), Wilson and Luxmoore (1988), and Dunn and Phillips (1991) found CVs increased as soil water pressure head decreased. Clothier and White (1981) and Ankeny et al. (1990) found the opposite. In addition to site-specific soil physical and biological factors, differences in CVs are sometimes caused by small sample numbers (Watson and Luxmoore 1986).Watson and Luxmoore (1986) and Wilson and Luxmoore (1988) measured the infiltration rate at four different soil water pressure heads at 37 and 39 locations, respectively, in two contrasting forested watersheds to study their spatial variability. In addition to creating arguable differences in CV of infiltration race at different soil water tensions (Watson and Luxmoore 1986). these small sample numbers were also less than the recommended minimum of 50 (Journel and Huijbregts 1978) needed co conduct any meaningful geostatistics. These earlier studies indicate it is imperative that more site-specific infiltration variability studies need to be conducted under different soil types and depositional environments (e.g., glacial till soil). Larger number of measurements (e.g., >50) are also needed to understand the spatial pattern of field-scale or watershed-scale infiltration process.

This study was designed with three objectives: (i) to measure and compare the infiltration rate, I,, at 0-, 30-, 60-, and 150-mm soil water tensions and its variability under three field positions, namely corn row, trafficked interrow, and nontrafficked interrow, across a row crop agricultural field in a glacial till depositional environment; (ii) to estimate the effective soil macroporosity and its contribution to field-scale infiltration, and (iii) co study the spatial variability of I, for three different field positions.

## FIELD EXPERIMENT

Infiltration measurements were made along two parallel transects running orthogonal to the crop rows in Field 5 at the Agronomy and Agricultural Engineering Research Center near Boone in central Iowa. Soil type in this field is predominantly silt loam that belongs to the Clarion-Nicollet-Webster soil association.Webster is a fine-loamy, mixed, and mesic Typic Haplaquoll located in the valley, and Clarion is a fine-loamy, mixed, mesic Typic Hapludoll located at the top of the hill. Nicollet, which is a fine-loamy, mixed, mesic Aquic Hapludoll, lies in midlevel positions between the other two. The soil was developed from calcareous glacial till (Des Moines lobe, Wisconsin age), with surface texture ranging from loam to sandy loam.All the measurements were limited to a plot under no-tillage management practice of continuous row-corn production for the last 8 years. This study was conducted in May 1990 during the planting season.

The automated tension infiltrometer (Ankeny et al. 1988) is useful for obtaining a large number of measurements, which in turn are necessary for determining spatial variability. This infiltrometer influences only a small area (7.62 cm diameter) of soil; therefore, it is useful for measuring infiltration rate in different soil management zones. Ponded and tension infiltrometers (Ankeny et al. 1988; Ankeny 1992) were used to measure infiltration rates along two parallel transects orthogonal to crop rows. Two parallel transects, one for corn row and the other for interrow measurement locations, were set 1 m apart to avoid any foot traffic at the measuring sites during the field experiment. The infiltrometers were run in sequence at the same position at 0-, 30-, 60-, and 150-mm water tensions, for 25 min with automatic recording of infiltration volume using pressure transducers and data loggers at regular time intervals. Infiltration measurements at 296 sites were completed in less than 1 week, minimizing the temporal variability in the data. Eighteen automated infiltrometers were used to accomplish all these measurements in this short time. Tension infiltrometer readings were taken at 160 corn row sites and I36 interrow sites (including trafficked and nontrafficked locations).

Figure 1 shows the five-row configuration of preplanting and harvesting traffic. The distance between consecutive rows and consecutive interrows was 76 cm. Infiltration measurements were made at the center of the corn rows and interrows. At each measurement location, an area approximately 25 to 30 cm in diameter was cleared to a depth of 2 to 3 cm and leveled.Two layers of cheesecloth were placed on the soil surface before wetting to minimize slaking of soil into the macropores. Flow measurements were taken from low to high tension (0 to 150 mm) on a 7.62-cm-diameter circle on the cleared soil surface, which allowed evaluation of surface position (treatment) effects on distribution of different pore sizes. Adopting the wet through dry (i.e., 0- through 150-mm tension) measurement sequence, the wetting front advances as rapidly as possible, and the assumption of unit gradient below the device is most valid. A total of 154, 152, 146, and 147 measurements were available from corn rows at 0-, 30-, 60-, and 150-mm tensions, respectively. Similarly, 60, 73, 74, and 63 data points were available for nontrafficked interrows, and 38,36,39, and 22, for trafficked interrows. Note, except for a few unsuccessful measurement sites, these numbers cover all surface positions in the entire field under study.

## DATA ANALYSIS

Statistical moments such as mean, standard deviation (SD), and coefficient of variation (CV) were calculated for each field position (treatment) at each tension by using SAS (SAS Inst. 1985). The Shapiro-Wilk test (Shapiro and Wilk 1965) was made to test the normality for each data set. Histograms were also drawn by using SAS to investigate the data distribution visually. Examination of these plots and w-statistics determines the more normal (raw or log-transformed) data for further geostatistical analysis of autocorreleogram estimation. Experimental autocorreleograms were estimated to quantify the spatial dependence/independence of the I, under each field position. Moran's statistic is defined as:

$$M^*(h) = N(h)\frac{\sum I_\psi(X_i)I_\psi(X_i+h)}{\sum I_\psi(X_i)^2} \qquad (1)$$

where

$M^*(h)$ = autocorrelation estimator for lag distance class $h$,

$I_\psi(X_i)$ = measured infiltration rate at point $X_i$,

$I_\psi(X_i+h)$ = measured infiltration rate at point $X_i+h$, and

$N(h)$ = total number of infiltration rate couples for the interval h.

## RESULTS AND DISCUSSION

### *Infiltration Rate*

In the glacial till soil, the spatial distribution of I, was highly variable, with values ranging more than an order of magnitude along the transect for 0-, 30-, 60-, and 150-mm tensions under corn row, nontrafficked interrow, and trafficked interrow positions (Fig. 2). Statistical moments of these I, data for different tensions and field positions (treatments) are presented in Table

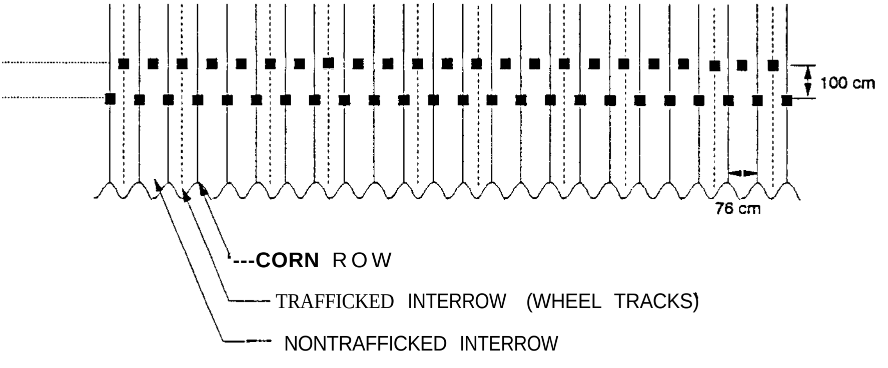


**Fig. 1. Five-row configuration of planting and harvest traffic in the row corn plot at the experimental site near Boone, Iowa. Solid squares indicate the infiltration measurement sites arranged on two parallel transects 1 m apart.**

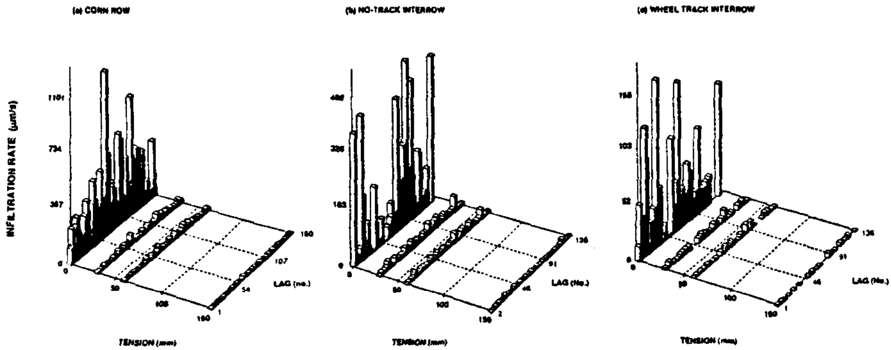


**Fig. 2. Spatial distribution of infiltration rate (µm/s) at 0, 30-, 60-, and 150-mm tensions along the transect under (a) corn row. (b) nontrafficked interrow, and (c) trafficked interrow positions. Blank spaces in** between measurements indicate missing data.

1. Multiple mean comparison (Duncan's test) showed that the mean relative infiltration rates for saturated condition, $I_0$, were significantly (P = 0.99) larger than $I_{30}$, $I_{60}$, and $I_{150}$ for all surface positions.The large decrease in mean infiltration rate from 0 to 30-mm tension indicates the dominance of macropores under saturated flow conditions. Nearly 91% (under corn row), 89% (under nontrafficked interrow), and 92% (under trafficked interrow) of the saturated water flux occurs through large pores and cracks associated with this tension interval. These values of macropore flow contribution, at three different surface positions under the no-till agricultural field in the glacial till soil, oumumbers some of the earlier research findings under different environmental setup. Watson and Luxmoore (1986) reported 73% of saturated flux through larger

**TABLE 1**

Summary statistics of I, (µm/s) at different tensions for corn row. nontrafficked interrow and trafficked interrow

| Moments | Tension = 0 mm | 30 mm | 60 mm | 150 mm |
|---|---|---|---|---|
| | | A. Corn Row | | |
| N | 154 | 152 | 146 | 147 |
| Mean | 179.69 | 16.59 | 12.46 | 4.98 |
| Standard deviation | 152.45 | 10.99 | 8.72 | 3.43 |
| Coefficient of variation (%) | 84.84 | 66.22 | 70.00 | 69.02 |
| W Normal† | 0.817 | 0.848 | 0.820 | 0.844 |
| | | B. Nontrafficked Interrow | | |
| N | 60 | 73 | 74 | 63 |
| Mean | 99.14 | I1.23 | 8.12 | 2.93 |
| Standard deviation | 123.38 | a.79 | 6.59 | 2.44 |
| Coefficient of variation (%) | 124.44 | 78.36 | 81.11 | 83.31 |
| W Normal† | 0.699 | 0.873 | 0.854 | 0.819 |
| | | C. Trafficked Interrow | | |
| N | 38 | 36 | 39 | 22 |
| Mean | 40.89 | 3.36 | 2.04 | 1.19 |
| Standard deviation | 38.67 | 2.27 | 1.92 | 1.04 |
| Coefficient of variation (%) | 94.57 | 67.66 | 94.34 | 87.54 |
| W Normal† | 0.825 | 0.920 | 0.783 | 0.862 |

†Normality test using the Shapiro-Wilk W statistics. Each data set was found not normally distributed at a confidence level >0.90.

pores in the same tension range (0 to 30-mm water tension) in a forested (Melton branch) watershed. In another study, Wilson and Luxmoore (1988) reported 83% (Walker branch forested watershed) and 75% (Melton branch forested watershed) contribution of flow through larger pores in a 0 to 20-mm tension range interval. Furthermore, Dunn and Philips (1991) conducted their study in a well drained agricultural field in Kentucky and found about 73 to 80% of the total water flux was transmitted through larger pores within a tension of 0.06 to 1.40 kPa. Similar to the forested watersheds ofWatson and Luxmoore (1986) and Wilson and Luxmoore (1988). and the agricultural watershed of Dunn and Phillips (1990). in our agricultural field, the relatively large contribution of macropores to water flow is probably caused by a combination of root channels, earthworm burrows, and the structural development of the soil matrix materials caused by wheel compaction and/or soil manipulation by agricultural equipment. Moreover, an important observation for all four tensions was made that mean infiltration rates were maximum under corn row, minimum under trafficked interrow, and intermediate under nontrafficked interrow positions.

### *Infiltration Rate-Variability*

When comparing different soil water pressure heads (Table 1). the coefficient of variation (CV) of the saturated infiltration rate (i.e., at O-mm tension) was found to be maximum under all three field positions indicating the large-pore variability associated with macropores and soil structure (aggregation).This finding agrees with Clothier andWhite (1981) and contradicts Watson and Luxmoore (1986), Wilson and Luxmoore (1988). and Dunn and Philips (1991). Thus, we suggest site-specific rather than general conclusions should be drawn from any (site-specific) study of this nature. Moreover, different surface positions showed different trends in CV across the range of tensions considered. In trafficked interrow, CV for O-mm and 60-mm tensions were almost equal and were higher than for 30-mm and 150-mm tensions. For saturated conditions, CV was greatest for nontrafficked interrow. less for the trafficked interrow in the middle, and least for the corn row. Increasing the tension (i.e., decreasing the pressure head) to 30 mm, the trend for CV remains the same as at saturation. Further increasing the tension, however, changes the CV trend. At 60-mm and 150-mm tensions, CVs were largest for trafficked interrow, intermediate for nontrafficked interrow. and least for corn row.The change in CV trend between nontrafficked and trafficked positions indicates a change in variability in the distribution of macro-, meso-, or micro-pore sizes. In other words, the results indicate that the distribution of smaller pores associated with variability of texture (particle-size distribution) is more variable under trafficked interrows than under nontrafficked interrows.

TABLE 2
Correlation coefficient matrix of infiltration rates at different tensions in the glacial till soil in central Iowa

| Tension | 0 mm | 30 mm | 60 mm | 150 mm |
|---|---|---|---|---|
| | | *A. Corn Row* | | |
| 0 mm | 1 | | | |
| 30 mm | 0.055 | 1 | | |
| 60 mm | 0.022 | 0.864 | 1 | |
| 150 mm | 0.005 | 0.648 | 0.715 | |
| | | B. Nontrafficked Interrow | | |
| 0 mm | 1 | | | |
| 30 mm | 0.217 | 1 | | |
| 60 mm | 0.169 | 0.929 | 1 | |
| 150 mm | 0.080 | 0.576 | 0.531 | |
| | | C. Trafficked Interrow | | |
| 0 mm | 1 | | | |
| 30 mm | 0.067 | 1 | | |
| 60 mm | 0.268 | 0.668 | 1 | |
| 150 mm | 0.111 | 0.181 | 0.696 | 1 |

*Infiltration Rate-Distribution*

Normality of I, at different tensions (0-, 30-. 60-. 150-mm) and under different surface positions (corn row, trafficked interrow. nontrafficked incerrow) was tested (shown in Table 1). No data set was distributed normally (for $P = 0.90$). $Log_e$-transformation was found to best describe **the data** distribution for all cases.Therefore, all data were transformed to log-scale for further spatial analysis.

Correlation analyses between the ponded infiltration rate ($I_0$) and infiltration races under tension ($I_{30}, I_{60}, I_{150}$) were made to investigate different scales of heterogeneity (Fig. 3). Under three surface positions, little correlation was found between saturated (ponded) infiltration race and infiltration under tension (see Table 2). However, better correlations were found among infiltration rates at different tensions (Table 2). Supported by maximum CVs for ponded infiltration (Table 1) in comparison with infiltration under tension, this observation may indicate two different scales of heterogeneity operating somewhat independently of each other. In other words, the scale of heterogeneity for in&ration at saturation is different from that of the infiltration under the tensions (30,60, and 150 mm) used in this study. Difference in the scale of heterogeneity probably indicates the difference in governing processes (e.g., ratio of gravity flow and capillary flow) for infilnation under different soil water tension ranges for the particular field setup.We suggest that gravity flow through larger pores dominates the infiltration process at saturation, whereas capillary flow dominates the infiltration process at tensions of 30 mm and below, adopting the Luxmoore (198 1) definition of macropore, mesopore and micropore for convenience. As flow measurements at different tensions were made under approximately steady-stare conditions, macropore conductivity (K,) was determined as the difference between the ponded infiltration rate ($I_0$) and the infiltration rate at 30-mm tension (I,). Based on this hypothesis, macroporosig for the glacial till soil at the experimental site was estimated (see Table 3) by applying Poiseuille's equation using the assumptions of laminar flow and cylindrical macropores of Watson and Luxmoore (1986). Note that the number and percentage of macroporosity are calculated by assuming the pores are of the minimum radius corresponding to the lower limiting tension of 30 mm and, therefore,

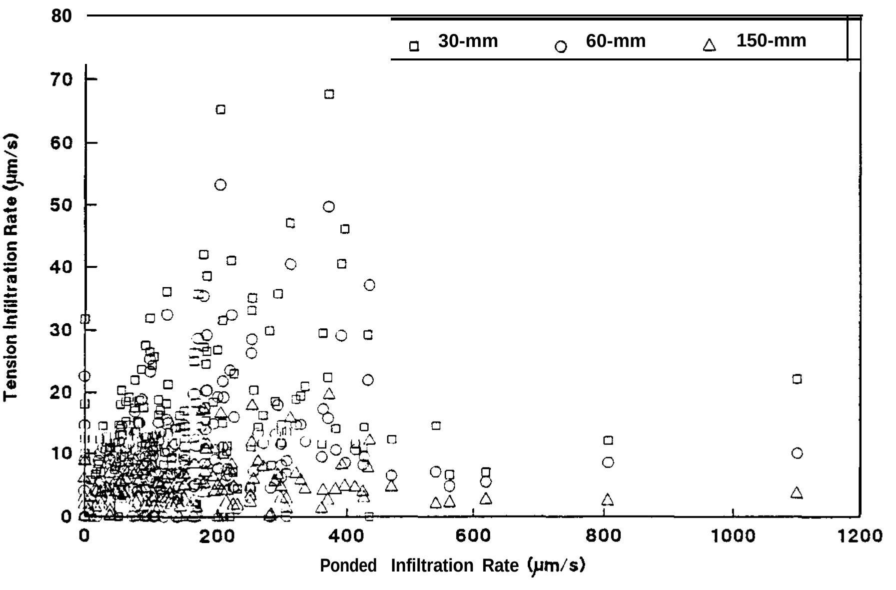


Fig. 3. Scatter **plot of ponded infiltration rate ($I_0$) versus tension** infiltration rates ($I_{30}, I_{60}, I_{150}$) **under corn row position indicating little correlation.**

TABLE 3

Macroporosity in the row corn field in the glacial till soil in central Iowa

| Treatment | No. of samples | Pore diameter† (mm) | No. of pores under the disc (1X2.4 cm') ‡ | % Area occupied by pores | % Flux through pores |
|---|---|---|---|---|---|
| Corn row | 152 | >I | 674 | 2.89 | 91 |
| Nontrafficked interrow | 60 | >I | 363 | 1.57 | 89 |
| Trafficked interrow | 36 | >I | 156 | 0.67 | 92 |

† The number of macropores and percentage porosity are calculated by assuming that pores are of the minimum radius of the tension range (30 mm) and therefore represent maximum values.

‡ Calculated using Poiseuille's equation

represent maximum values. Results indicate that under all three surface positions, less than 3% of the total surface area contributes to approximately 90% of the total water flux. Moreover, under all three field positions, the relative contribution of macropores to water flow appears to be correlated with the ponded flow rate (Fig. 4).This correlation implies that as the mean velocity increases, a relatively small fraction of the total pore space is conducting a relatively large fraction of water. This simply signifies the importance of macropore flow in the infiltration process in the agricultural field under investigation.

### Infiltration *Rate-Spatial Structure*

Autocorrelation estimates were made for different surface positions and different tensions and plotted in Fig. 5.The number of lags was limited to a quarter length of the transects in order to have more than 50 pairs for each autocorrelation **estimate,** except under the trafficked position. For all surface positions and soil water heads, auto-

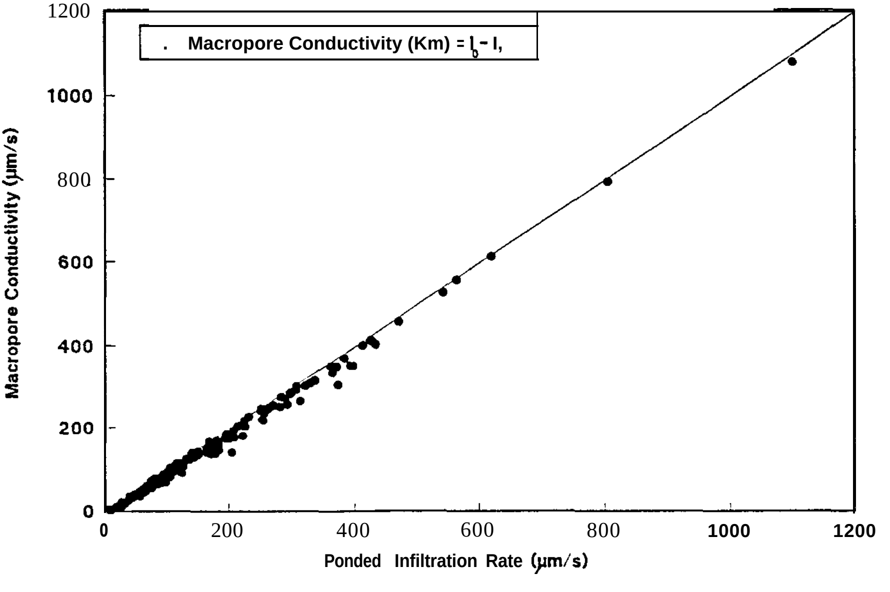


Fig. 4. Correlation between ponded infiltration rate ($I_0$) and macropore conductivity ($K_m$) under corn row position.

correlation estimates showed large contribution of random variation. Overall, examination of these figures indicated little spatial dependence under all three surface positions and four negative soil water heads. Comparison of Fig. 5a (corn tow) with Figs. 5b (nontrafficked interrow) and 5c (trafficked interrow), however, indicates better spatial dependence for the corn row position than for the other two. In addition to a large amount of microheterogeneity, a small structure of 10 to 15 row counts (7.6 m to I I.4 m) is observable in the autocorreleograms under corn row. Although the exact reason is unknown, we suggest that the farming and wheel traffic history in this field may be the possible reason for this behavior. Spatial structure was most evident at saturated condition (O-mm tension) and least evident at 150-mm tension under corn row. And the ***structure for*** 30-mm and 60-mm ***tension*** lies somewhere between the ocher two.This finding gives ***a very*** valuable insight to the (surface) infiltration process. In the row crop agricultural field under study, under corn row position, larger pores (macmpores) that conduct water at saturation are spatially better correlated than are the smaller pores that conduct water at the negative soil water heads. Under (nontrafficked and trafficked) interrow positions, when no spatial structure but random variation exists for infiltration at 0-, 30-, and 60-mm tensions, evidently, a small spatial structure of approximately 10 intermw counts (7.6-m range) exists for infiltration at 150-mm tension.This may be argued because matrix-pores are spatially better correlated than macropores and mesopores under intermw positions.

## SUMMARY AND CONCLUSIONS

In a glacial till soil, infiltration measurements were made at 0-, 30-, 60-. I50-mm tension at 296 sites under corn rows, nontrafficked inter-***mws,*** and trafficked intermws along two parallel transects orthogonal to corn rows. Infiltration at saturation ($I_0$) was found co have a different scale of heterogeneity than infiltration at other tensions ($I_{30}$, $I_{60}$, $I_{150}$) under all ***surface*** positions (corn row, nontrafficked interrow, and trafficked interrow). Moreover, less than 3% of the total surface area associated with macropores (>1-

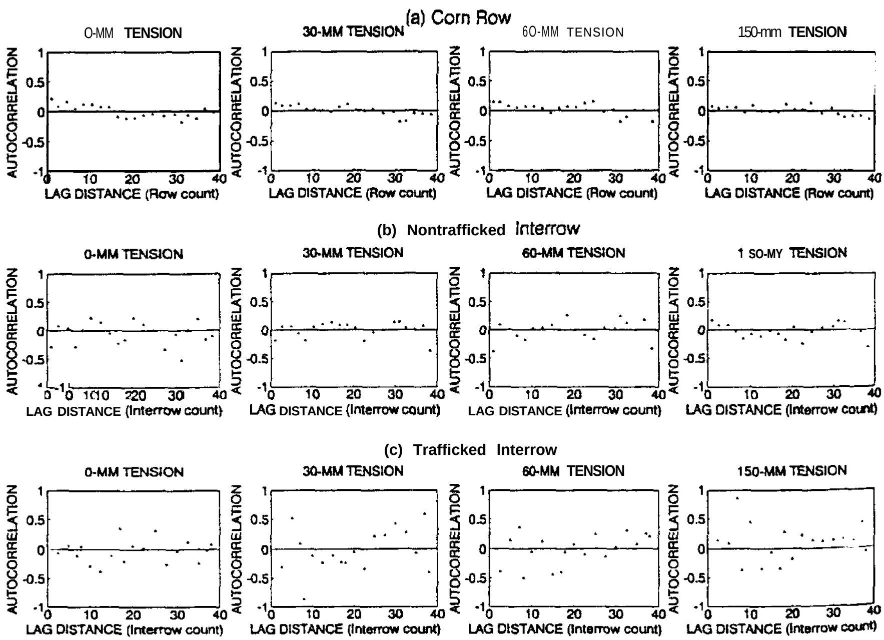


**Fig. 5. Sample autocorreleograms of $I_\psi$ under corn row (a), nontrafficked interrow (b), and trafficked interrow (C) positions at O-mm, 30-mm, 60-mm, and 150-mm tension.**

mm diameter) accounts for nearly 90% of the total saturated water flux. Infiltration at smaller tensions (0 mm **and** 30 mm) are more variable under nontrafficked interrows than under trafficked interrows. On the other hand infiltration at high tensions (60 mm and 150 mm; i.e., smaller pores) are more variable under trafficked interrows than under nontrafficked interrows. Spatial analysis of infiltration rate showed a large proportion of random variation and a small spatial structure of approximately 7.6 to 11.3-m range at different soil water tensions under corn row position. Under (nontrafficked and trafficked) interrow positions, no spatial structure was found for macro- and meso-pore flow (at 0- to 60-mm tension). However, in addition to large random variation, a small spatial structure of about 7.6-m range was found for matrix-flow at 150-mm tension under interrow positions. Consequently, infiltration rates and their variability, including spatial correlation structures in matrix and macropore regions, could be used for field-scale solute transport modeling using a multi-domain flow concept.

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