Simultaneous and Continuous Measurement of Soil Water Content and Solution Electrical Conductivity in an Irrigated Cornfield Using TDR

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Simultaneous and continuous measurements of volumetric soil water content and soil solution electrical conductivity made using time domain reflectometry (TDR) sensors in an irrigated cornfield in the Yellow River basin, Inner Mongolia, China, were analyzed. The results are summarized as follows:
(a) Cumulative depth of water supplied to the root zone from a water table in spring and early summer of little rain was estimated to be about 80 mm, which may be traced to the irrigation water applied last autumn.
(b) When soil water moved upward from a water table to the soil surface during a period of little rain, soluble salts in the groundwater were transported through the root zone up to the soil surface.
(c) When basin irrigation was applied or a heavy rain occurred, part of the water applied flowed down quickly through macropores before much of the salt accumulated at the surface was dissolved in it. On the other hand, the rest of water in which the accumulated salt was fully dissolved moved slowly through smaller pores.
(d) When a large amount of water was applied to the soil surface, soluble salts in smaller pores moved downward quickly for a short distance and stayed at some lower depths. It can be reconfirmed from this result that small, intermittent applications are more effective for salt leaching than continuous flooding applications are.

Keywords: Soil electrical conductivity, Irrigation, Soil salinity, Soil water content, TDR, Yellow River

I. INTRODUCTION

The transport of soluble salts through unsaturated field soils is directly related to the movement of water, but our understanding of the process is limited because of the lack of experimental data (Kachanoski et al., 1992). Simultaneous and continuous in situ measurement of volumetric soil water content ($\theta$) and soluble salt concentration ($c$) is essential to clarify the distribution and movement of salts in the soil profile under cropped conditions. Volumetric soil water content and electrical conductivity of bulk soil ($EC_b$) can be measured simultaneously using a time domain reflectometry (TDR) sensor (Dalton et al., 1984; Dirksen, 1999). Furthermore, electrical conductivity of soil solution ($EC_s$), from which soluble salt concentration is estimated with good accuracy (Tanji, 1990), can be calculated from $\theta$ and $EC_b$ using a model equation (Wang et al., 2005). Therefore it is possible to measure $\theta$ and $c$ simultaneously and continuously at a point in the field using a TDR probe.
Noborio et al. (1996) measured the distributions of $\theta$ and $c$ in furrow-irrigated soil using TDR probes, when, however, they replaced the original topsoil 0.6 m thick with loamy sand to ensure the homogeneity of soil. Water and solute transport processes in heterogeneous field soils are affected significantly by spatial and temporal variations in soil hydraulic conductivity (Edwards et al., 1992; Campbell et al., 2001). Bergstrom and Shirmohammadi (1999, as cited by Shirmohammadi et al., 2005) showed that models describing water and solute transport through structured soils must consider preferential flow-induced bimodal transport instead of using classical concepts of "piston flow" and "convective-dispersive" transport. New concepts for structured soils such as three-domain flow that is assumed to take place in three domains; i.e., micropores (immobile zone), mesopores (slow flow region) and macropores (fast flow region), have been presented (Shirmohammadi et al., 2005). However, Darcian approaches and such new concepts either fail in the proper mathematical presentation of the system of preferential flow, and further investigation is needed to develop appropriate mathematical algorithms (Shirmohammadi et al., 2005).

This paper describes the results obtained by analyzing the simultaneous and continuous measurements of $\theta$ and $EC_w$ made with TDR sensors deployed in an irrigated cornfield in the Yellow River basin. Corn roots extend to below 1 m depth and remain as the residue in the field soil every year and make a lot of macropores. Therefore, the data are analyzed based tentatively on the concept of two-domain flow; that is, water and salt transport is assumed to take place in two domains, macropores (fast flow region) and smaller pores (slow flow region).

II. EXPERIMENT

Japan Science and Technology Agency (JST) and Institute of Agro-Environment and Sustainable Development, CAAS, China established jointly an experimental field at Togtoh (Lat. N 40°14.8’, Lon. E 111°11.0’, Alt. 995 m) in Hohhot, Inner Mongolia, China, for carrying out irrigation experiments (Iwanaga et al., 2005). This field is located in the alluvial valley of the upper Yellow River and consists of a 55 x 73 m area that is divided into a few plots surrounded by borders to facilitate ponding (Fig.1). In this area basin irrigation is applied with the water diverted from the Yellow River. The soil profile is made up of alluvial soil layers, and a thin layer of clayey soil is sandwiched between them at a depth of 60 ~ 80 cm. The physical properties of the alluvial soil are shown in Table 1.

![Fig. 1 Plane figure of Togtoh experimental field.](image)
Numbers in parentheses indicate the relative heights of the soil surface to that at an observation well, #1, and the shaded area of the irrigation canal indicates the section paved with concrete.

<table>
<thead>
<tr>
<th>Particle size (mm)</th>
<th>% by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.002</td>
<td>10.3</td>
</tr>
<tr>
<td>0.002 ~ 0.075</td>
<td>67.5</td>
</tr>
<tr>
<td>0.075 ~ 0.25</td>
<td>17.3</td>
</tr>
<tr>
<td>0.25 ~ 0.85</td>
<td>0.2</td>
</tr>
<tr>
<td>0.85 ~ 2</td>
<td>4.7</td>
</tr>
</tbody>
</table>

| Particle density (g cm$^{-1}$) | 2.70 |
| Dry density (g cm$^{-3}$)      | 1.35 |
| Porosity (-)                   | 0.50 |
| Saturated hydraulic conductivity (cm s$^{-1}$) | $1.29 \times 10^{-4}$ |
Meteorological and hydrological observations were made in the field from the end of April 2003 to the end of March 2006, and the data obtained in 2003 and 2004 are used in this study. Variables observed and instruments used are summarized in Table 2. Soil dielectric constant ($K_a$) and $E_{Ca}$ were measured using TDR. The TDR probe (CAMPBELL, CS-610) has the wave-guide consisted of three rods of 30 cm long, 0.48 cm diameter and 2.2 cm spacing. The probes were installed at 3 or 5 depths of three points (P1, P2, P3) and at one depth of one point (W.S.) (Table 3). They were inserted horizontally so that the three rods were laid in a horizontal plane. The measurements of $K_a$ and $E_{Ca}$ were taken on the hour (Beijing Standard Time).

Substitution of the measurements of $K_a$ and $E_{Ca}$ into the following model equations determined by Wang et al. (2005) for this alluvial soil gives $\theta$ and $E_{Ca}$.

$$\theta = 1.65 \times 10^{-5} K_a^2 - 9.91 \times 10^{-4} K_a^2 + 3.32 \times 10^{-2} K_a - 4.8 \times 10^{-2}$$ (1)

$$E_{Ca} = E_{Ca} \cdot (1.013 \theta - 0.074) + 0.08 (d S m^{-1})$$

Every value of $E_C$ was normalized to a temperature of 25°C.

Corn (*Zea mays* L.) was planted on 4 May 2003 and 27 April 2004, the variety being Zhedan (in Chinese) No.7, and was harvested at the beginning of October in both years. Root distribution within the soil profile was measured by examining the soil samples removed in increments to a depth of 100 cm four times in the growing season. Root weights obtained by washing the soil samples through a 0.5-mm sieve showed almost all roots measured were in the upper 80 cm (Iwanaga et al., 2004). Therefore the depth of the root zone is assumed to be 100 cm at most in this study. Basin irrigation was applied on 29 July and 20 August in 2003, and on 16 July in 2004. Post-harvest (autumn) irrigation was applied on 30 October 2003 and 28 October 2004 to leach salts from the root zone and also to hold part of irrigation water over winter within the frozen soil layer and the aquifer to provide crops with water for their germination and emergence in the coming spring of little rain (Kaneko et al., submitted).

## III. RESULTS AND DISCUSSION

### 1. Seasonal variations in $\theta$ and $E_{Ca}$

Simultaneous and continuous measurements of $\theta$ and $E_{Ca}$ made at P1 in 2004 are given in Fig.2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Instrument</th>
<th>Height &amp; Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature &amp; Humidity</td>
<td>CAMPBELL, CS500-L6</td>
<td>1.16, 2.52, 3.81, 5.79</td>
</tr>
<tr>
<td>Net radiation</td>
<td>CAMPBELL, Q7.1-L20</td>
<td>3.79</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>CAMPBELL, CS105</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>CAMPBELL, 03101-L11</td>
<td>2.50, 3.90, 5.76</td>
</tr>
<tr>
<td>Precipitation</td>
<td>CAMPBELL, CS700-L25</td>
<td></td>
</tr>
<tr>
<td>Groundwater level</td>
<td>CAMPBELL, CS420-L</td>
<td></td>
</tr>
<tr>
<td>Soil temperature</td>
<td>CAMPBELL, MODEL 107</td>
<td>-0.1, -0.2, -0.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Period</th>
<th>Point &amp; depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
</tr>
<tr>
<td>27 Apr. 2003 ~ 23 Apr. 2004</td>
<td>10,20,40</td>
</tr>
<tr>
<td>24 Apr. 2004 ~ 5 Nov. 2004</td>
<td>10,20,40,60,100</td>
</tr>
<tr>
<td>6 Nov. 2004 ~</td>
<td>10,20,40,60,100</td>
</tr>
</tbody>
</table>
as an example. The first irrigation was applied on 16 July, and the second (autumn) irrigation on 28 October. Seasonal variations in daily precipitation and the depth of the water table at an observation well (#1) are also shown in Fig.3. The top 100 cm of the profile seems to be divided into three layers; a surface layer 0 ~ 20 cm, a transition layer 20 ~ 60 cm and a lower layer 60 ~ 100 cm. The lower layer contained always enough water to be available for plant roots, while soil water depletion was severe in the surface layer in June and the first half of July. This clear difference between the lower layer and the surface layer may be attributed to the existence of a thin layer of clayey soil at a depth of 60 ~ 80 cm. More work is needed on this matter, however. \( \text{EC}_a \) changed almost in phase with \( \theta \), which demonstrates that \( \text{EC}_a \) is related closely to \( \theta \) as is inferred from Eq.(2).

Let us use the mean value of the measurements made at two depths of 20 cm and 40 cm as a representative value of the main root zone in the analyses described here and in 3. Fig.4 shows the seasonal variations in \( \theta \) and \( \text{EC}_a \) in the main root zone at P1, P2 and P3 in 2003. Fig.5 shows the seasonal variations in daily precipitation and the depth of the water table at #1 during the same period as in Fig.4. Both \( \theta \) and \( \text{EC}_a \) exhibited
rapid increases or jumps at the times when irrigation was applied or a heavy rain occurred, which seems to have resulted from macropore flows. During the time of little rain soil water was depleted most severely at P2, while during the period after irrigation, \( \theta \) was the largest at P3 but it was not the case after rain events, which suggests that this phenomenon was due to the fact that the soil surface at P3 is lower than the other points (Fig.1). Spatial variation in soil wetness was large in the field when \( \theta \) was very low or very high after irrigation. The formation of frozen soil layers is responsible for the rapid decrease in \( \theta \) at the beginning of December. The EC_a at P2 was smaller than those at the other points in most of the period, which implies that soil salinity was the lowest at P2 among the measurement points. This is confirmed below in Fig.7.

2. Seasonal variation in vertical water flux

It is difficult to evaluate accurately the water flux resulting from irrigation or a heavy rain because the velocity of water flow through macropores is too large to be measured with the observation system installed in this experimental field. This phenomenon can be confirmed in Figs. 3 and 5 in which the depth of a water table arose and reached a peak within a day after irrigation. Therefore we have to exclude the macropore flows arising directly from irrigation or a heavy rain from this analysis.

Water balance for a soil layer with thickness \( D \) is written as follows:

\[
W(t + \Delta t) - W(t) = \Delta W(t) = f_w(t, z + D) - f_w(t, z) - Ru(t; z, z + D)
\]

where

\[
W = \int_{-z}^{z+D} \theta \, dz
\]

\( t \) is time in weeks, \( f_w(z) \) the water flux (positive upward) at depth \( z \) (positive downward) and \( Ru \) the flux equivalent to the root water uptake in the layer.

We assume the following relations to a first approximation, but this is a matter requiring further investigation (Feddes et al., 2000; Prasad, 1988).

\[
f_w(t, 0) = \frac{1}{t} E(t)
\]

\[
Ru(t; z, z + D) = \frac{E(t)}{D_{root}} \int_{z}^{z+D} \left(1 - \frac{z}{D_{root}}\right) dz
\]

where \( E(t) \) indicates weekly actual evapotranspiration, which was measured by the Bowen ratio method (Iwanaga, 2005), \( D_{root} \) the thickness of the root zone (100 cm in this study).
Fig. 6 shows the weekly soil water fluxes at depths of 40 cm and 100 cm calculated using the measurements of $\theta$ made at P1, weekly precipitation and actual evapotranspiration. Spring and early summer are seasons of relatively little rain, and hence soil water moves upward from a water table to the root zone. Cumulative water depth supplied to the root zone, the lower boundary being assumed to be the 100-cm depth, from the water table was estimated to be about 80 mm during the period from the planting of corn to the first irrigation practiced on 16 Jul. 2004. Kaneko et al. (2006) showed that this accounted for about 80 % of the water depth irrigated last autumn and carried over winter. In the flowering and yield formation periods in summer, water flux through the lower boundary of the root zone was basically negative (downward), which seems to have reflected the water-table decline (Fig.3) because $\theta$ was about 0.5 or degree of saturation was almost 100 % at depths below 60 cm during these periods (Fig.2 a).

In this analysis it was assumed that soil surface evaporation was responsible for half the actual evaporation (Eq.4), but this is not true but a matter requiring further investigation. Therefore, the fluxes through the 40-cm depth are shown in Fig.6 only for reference. However, the estimate of flux through the 100-cm depth is independent of this assumption.

3. Seasonal variations in $E_{C_w}$ and $E_{C_{SAT}}$

Fig. 7 shows the seasonal variations in $E_{C_w}$ and the electrical conductivity of the extract of a saturated soil ($E_{C_{SAT}}$) in the main root zone at P1, P2 and P3 in 2003. $E_{C_{SAT}}$ is an index that measures the amount of salts dissolved in soil solution (Kobayashi et al., 2006). They are the means of measurements made at two depths of 20 cm and 40 cm as mentioned in 1. $E_{C_w}$ exhibited a seasonal variation with larger values in the four months of July through October, which seems due to the salts left behind in the soil profile when plant roots extracted soil water and evaporation occurred at the soil surface. However, $E_{C_w}$ or soluble salt concentration decreased abruptly when irrigation was applied or a heavy rain occurred, though the extent of the decrease differed from location to location. This suggests that the salt concentration of the water flowing down the profile quickly was on the average lower than that of the soil solution in the main root zone.

On the other hand, $E_{C_{SAT}}$ was almost constant in time before the first irrigation applied on 29 Jul. 2003 but increased abruptly at the times when the first and the second (20 Aug. 2003) irrigations were applied, which suggests that most of these increases in soluble salts were transported into the root zone from the soil surface in which much salts had been accumulated before the first irrigation. The third (autumn) irrigation applied on 28 Oct. 2003, however, reduced $E_{C_{SAT}}$ immediately at all the three points, which means that this large irrigation leached salts from the root zone directly and simultaneously.

These results suggest that the salts precipitated on soil particles in the profile, especially in the surface were dissolved in irrigation water when the first and second irrigations were applied, and part of the salts dissolved moved down quickly through macropores and the rest of them moved down slowly through smaller pores when the soil water status in the root zone was above field capacity. After the autumn irrigation was applied, the $E_{C_{SAT}}$ of the surface soil (Table 4) was almost the same as that of irrigation water of about 1 dS m$^{-1}$ (Kaneko et al., 2005). Furthermore, the $E_{C_{SAT}}$ observed in the main root zone, especially at P2, was also nearly equal to 1 dS m$^{-1}$. Hence, it is surmised that the autumn irrigation water dissolved all the salts accumulated at the surface in it, and also changed places with the soil solution containing much salts in the main root zone (Fig.7).

Table 4 The measurements of $E_{C_{SAT}}$ of the surface soil in the vicinity of P1 in 2004.

<table>
<thead>
<tr>
<th>Date</th>
<th>26 Apr.</th>
<th>1 Jul.</th>
<th>23 Aug.</th>
<th>1 Nov.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{C_{SAT}}$ (dS m$^{-1}$)</td>
<td>11.2</td>
<td>19.1</td>
<td>0.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>
shows the seasonal variations in ECw and ECSAT at depths of 20 cm and 40 cm of P1 in 2003.

**4. Vertical movement of soluble salts**

Fig. 8 shows the seasonal variations in ECw and ECSAT at depths of 20 cm and 40 cm of P1 in 2003. The data could not be taken at the 10-cm depth because the soil became too dry to use Eq.(2) for evaluating ECw. The ECw and ECSAT at the 20-cm depth were larger than those at the 40-cm depth except for a short period in summer. Soluble salts may have been transported downward from the surface by a complicated dynamic process described below during the period. ECw gradually increased from late in spring to summer, however ECSAT hardly increased until a heavy rain occurred or irrigation was applied. The gradual increase in ECw during this period was due to the decrease in soil water content caused by plant root extraction and by diffusive upward transport of water vapor attributable to soil surface evaporation. Since water moved upward from a water table to the soil surface before the first irrigation, ECSAT being held constant means that a fair amount of salts was transported through the root zone up to the surface and accumulated there.

**Table 4** shows the measurements of ECSAT of the surface soil made by taking soil samples in the vicinity of P1 in 2004 (not in 2003)(Kobayashi et al., 2006), which substantiates the salt accumulation at the soil surface before the first irrigation practiced on 16 July in 2004 and the dissolution after it.

The ECw at the 20-cm depth increased stepwise at the times when a heavy rain occurred or irrigation was practiced and decreased thereafter, while that at the 40-cm depth increased a little on 30 July when a 10-cm irrigation was applied but exhibited a large increase or a jump on 20 August when a more than 10-cm irrigation was applied. This suggests that soluble salts in smaller pores usually moved slowly, but downward quickly when a large amount of water was applied to the surface, and stay at some lower depths in the root zone. The depths at which soluble salts accumulate will depend on the soil water status and the amount of irrigation water or rainfall and others.

This kind of phenomenon emerged more clearly in the results obtained in 2004. Fig. 9 shows the seasonal variations in ECw and ECSAT at depths of 10, 20 and 40 cm of P1 in 2004. The periods when $\theta$ was smaller than 0.15 were excluded from this analysis because Eq.(2) cannot be used to estimate
EC\textsubscript{w} under such a condition. Seasonal variations in daily precipitation and the depth of the water table at #1 during this period are shown in Fig.3. Although EC\textsubscript{w} increased as the water content decreased before the first irrigation (16 Jul. 2004), EC\textsubscript{SAT} kept almost constant over the period and even being on the decrease in June as in the case of 2003. Just after the first irrigation EC\textsubscript{w} decreased abruptly and then increased during the subsequent several days at the 20-cm depth and a few months at the 40-cm depth. The situation at the 10-cm depth seems almost the same as that at the 20-cm depth, though they are not shown because of the poor accuracy of estimating EC\textsubscript{w} under a dry condition. Miller \textit{et al.} (1965) observed a phenomenon similar to this but they thought of the behavior as associated with the sampling technique they used. Porous ceramic cups were used to take solution samples in their experiment. However, it is not the case in the present experiment.

These results lead to the supposition that irrigation water is separable into two parts; one including soluble salts in relatively low concentration and flowing down quickly through macropores, and the other including soluble salts in relatively high concentration and moving down slowly through smaller pores. The soil solution at the three depths was diluted first with the first kind of water including little dissolved salts, however the second kind of water including much dissolved salts followed behind. During the period of much rain after the first irrigation, EC\textsubscript{w} decreased at depths of 10 cm and 20 cm but kept increasing gradually at the 40-cm depth.

On the other hand, the time changes in EC\textsubscript{SAT} at the three depths were related in an interesting way with each other. Just after the first irrigation EC\textsubscript{SAT} increased simultaneously at the three depths, but a peak at the 10-cm depth appeared first and that at the 20-cm depth followed. However a peak did not appear at the 40-cm depth until 20-21 August when 47.2 mm of rainfall was recorded and the groundwater table at #1 rose up to about 1.5 m below the surface (Fig.3). EC\textsubscript{SAT} increased abruptly at the 40-cm depth on 21 Aug. 2003. The estimates of EC\textsubscript{SAT} made at depths of 60 cm and 100 cm showed almost the same variation patterns as that at the 40-cm depth, though they are not shown because the water contents at the two depths were much larger than 0.4 (the upper limit of the application range of Eq.2) (Fig.2) and hence the accuracy of estimating EC was unsatisfactory.

On 22 August the depth of a water table and the EC of groundwater were measured at #1 and #2 (Fig.1) by chance in the field. The level of the water table at #2 was 5 cm higher than that at #1 (Fig.3) and the EC measurements of groundwater taken at #1 and #2 were 1.23 dS m\textsuperscript{-1} and 4.87 dS m\textsuperscript{-1}, respectively. We were surprised at this big difference in EC between the two observation wells, and repeated the measurement but got the same results. Furthermore, P5 located in a salt-affected field (Fig.1) was submerged under water because of ill drainage. Therefore this phenomenon cannot be interpreted as a simple one-dimensional process, but it may be supposed that there were more than two masses of groundwater with different salt concentrations and they moved in complicated manners.

As long as a water table is deep enough so that the distribution and movement of soil water in the vadose zone can be regarded as an one-dimensional process, it seems reasonable to conclude that soluble salts in smaller pores are transported slowly, of course downward when soil water status is above field capacity, but when a large amount of water is applied to the surface the soluble salts in smaller pores move downward quickly for a short distance and stay at some lower depths.

\section{CONCLUDING REMARKS}

Simultaneous and continuous measurements of $\theta$ and EC\textsubscript{w} were made using TDR in an irrigated cornfield in the Yellow River basin, Inner Mongolia, China, in order to clarify the distribution and movement of water and salts under cropped conditions. The results are
summarized as follows:

(a) Cumulative depth of water supplied to the root zone from a water table in spring and early summer of little rain was estimated to be about 80 mm, which may be traced to the irrigation water applied last autumn (Kaneko et al., 2006).

(b) When soil water moved upward from a water table to the surface during the vegetative period of little rain, the ECw in the root zone increased due to soil water depletion by plant root extraction and soil surface evaporation but the total amount of salts dissolved in soil solution measured by EC_{SAT} was nearly constant in time. This means that soluble salts contained in the groundwater were transported through the profile up to the surface.

(c) When basin irrigation was applied or a heavy rain occurred, part of the water applied to the surface flowed down quickly through macropores before much of the salt accumulated at the surface was dissolved in it. On the other hand, the rest of water in which the accumulated salt was fully dissolved moved slowly through smaller pores.

(d) An abrupt increase in the total dissolved salts measured by EC_{SAT} was often observed at some depths in the root zone when a large amount of water was applied to the surface, which seems to suggest that soluble salts in smaller pores moved downward quickly for a short distance and stayed at some lower depths.

Miller et al. (1965) investigated the manner in which chloride, applied to the surface as KCl, moves through clay loam under field conditions, and revealed that chloride movement results from a dynamic process that may be altered or controlled with the method of water application. For example, intermittently ponding the soil with 2-inch increments of water was markedly more efficient in leaching the applied chloride from the profile than continuously ponding the soil with water was. These phenomena may be related to those observed in the present experiment. It can be reconfirmed from this result that small, intermittent applications are more effective for salt leaching than continuous flooding applications are (Tanji, 1990).

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灌漑トウモロコシ畑におけるTDRによる含水量と溶液導電率の同時連続測定

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黄河流域（中国・内モンゴル）の灌漑トウモロコシ畑において、TDRセンサーを用いて体積含水量と土壤溶液導電率を同時連続測定し、解析した。その結果は以下のように要約できる。
(a) 降水量の少ない春から初夏にかけて、地下水位から根域へ供給された積算水分量は約80mmと推定された。これより前年秋に加えられた灌漑水に由来するものと思われる。
(b) 少雨期に土壤水分が地下水位から根域表面まで圧縮する際、地下水に含まれる塩分は根域を通過して土壤表面まで達れた。
(c) 灌漑が行われ、あるいは強雨が発生したとき、加えられた水の一部は、土壤表面の集積塩分の多くが新しい流下前に、大間隙を通じて速やかに流下した。一方、集積塩分が十分溶け込んだ残りの水は、小間隙内をゆっくり移動した。
(d) 土壤表面に大量の水が加えられると、小間隙内の塩分は短距離間急激に流下し、より下層へ集積した。この結果から、塩分のリーチングに対しては、連続灌漑灌漑よりも少量間断灌漑の方が有効であるということが再確認できる。

キーワード：土壤導電率、灌漑、土壤塩度、土壤含水量、TDR、黄河


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