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WATER AND SALT MOVEMENTS IN SIMULTANEOUS FLOOD-IRRIGATION AND WELL-DRAINAGE OPERATIONS *

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ABSTRACT: This paper describes a new technology for solonchak soil reclamation in which surface flood irrigation of fresh water and pumped wells drainage of salty groundwater are combined. The comprehensive investigation of water and salt movement has been conducted through field test, laboratory simulation and numerical calculation. The dependence of desalination on irrigation water quantity, drainage quantity, leaching time and other parameters is obtained based on the field tests. The entire desalination process under the flood-irrigation and well-drainage operations was experimentally simulated in a vertical soil column. The water and salt movement has been numerically analyzed for both the field and laboratory conditions. The present work indicates that this new technology can greatly improve the effects of desalination.

KEY WORDS: water and salt movements, solonchak soil reclamation, irrigation-drainage method

1 INTRODUCTION

In the Huang-Huai-Hai Plain of North China, there is still a large amount of unproductive lands due to soil salinization and alkalinization. For example, Beiqiu at Yucheng County of Shandong Province, where the territory is very flat and low-lying with drainage difficulty has vast saline and alkaline lands. During 1970 s~1980 s, several tests were made for integrated management and reclamation of the lowlands, but the improvement of saline depression was not satisfactory. Since 1989, solonchack soil reclamation project has been carried on at Yucheng Integrated Experimental Station of the Chinese Academy of Sciences. In the first test program conducted in the spring of 1989[1], they selected a typical 2 ha waste land of high salt content in the central zone of Beiqiuwa and began a series of rapid soil improvement tests. Prior to the test, soil salinity of the land was high, up to 1.9% in its surface layer and more than 0.6% in its topsoil. This land was covered by a thin crystallized salt crust. The mineralization of its groundwater was about 6 g/l. In order to wash down the salts, an intensive leaching method was employed: surface flood irrigation of fresh

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water and pumped wells drainage of salty groundwater were combined. After a three-week flood-irrigation and pumped-drainage operation, the crystallized salt crust disappeared in the surface layer and the salt content in the topsoil became lower than 0.2%. As a result, the corn yield reached 4.5 t/ha that year.

For further investigating the mechanism of the intensive irrigation-drainage method, the second program was started in May of 1990. This program consisted of field tests, laboratory experiments and numerical calculations to study the phenomena of water and salt movement in soil.

2 DESCRIPTION OF INTENSIVE LEACHING TEST AT THE SITE

During May of 1990, the second field tests of flood irrigation and pumped well drainage was completed at Beiqiuwa Experimental Zone. One drainage canal and fourteen pump-wells were distributed over this 0.8 ha land. These shallow wells of 5 m in depth were arranged in two rows with 24 m row spacing and 20 m spacing between the columns. At first, the simultaneous flood irrigation and pump drainage operations continued for five days, the test field was irrigated with a total amount 450 mm of water. After three days of only pump drainage operation, another water supply of 150 mm was provided. Again, the irrigation operation stopped but the pump drainage continued for another two days. Then the field test was completed. Hence, The total quantity of irrigation water was 600 mm and the average infiltration rate was 0.384 cm/h while the drainage water quantity was 300 mm. During the irrigation period, surface water of 5 cm~10 cm in depth remained on the test areas. To determine the leaching effects, various monitoring apparatus were installed in the test field. Some salt transducers were buried under the ground at different depths. Besides, there were a neutron detector tube and an observation well respectively for measuring the soil water content and underground water level.

The variations of soil salinity and salt concentration during the test period are given in Figs.1 and 2, showing that the salt in the topsoil is significantly washed down and salt-accumulated layer disappears in the soil of depth less then 1.5 m. According to water mass balance, irrigation water flows down mainly into the groundwater, some is pumped out by the shallow wells and some seeps into the drainage canal. Consequently, in the form of soil solution, the majority of salt goes into the underground water, some are pumped out while some of the salts percolate into the drain. In this way, the topsoil was quickly desalted to some extent even for the shallow ground water. In addition, some observation wells were arranged around the pumping wells to monitor the table level and mineralization of the groundwater. The observation results are shown in Fig.3. It is seen that the groundwater level and its mineralization decrease as the distance from the pumping decreases.

As compared with the result of the first field tests (see Fig.2), The overall effects of salt leaching for these two tests are similar. However, the total irrigation water increases from 450 mm in the 1989 test to 600 mm in the 1990 test, while the leaching duration decreases from 21 days to 10 days. It attributes the difference to the irrigation model:

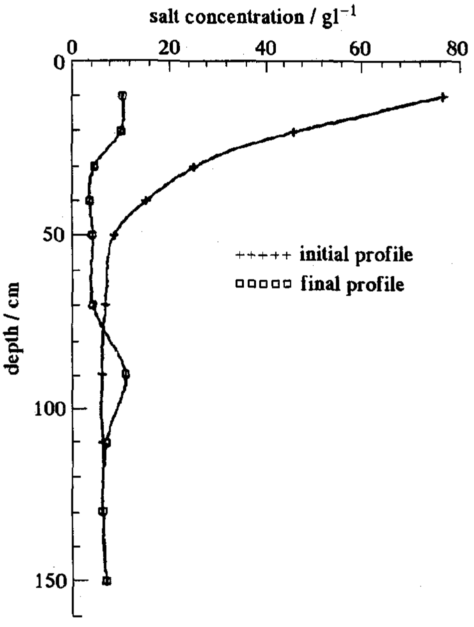

Fig.1 The Salt Concentration Profiles before and after leaching

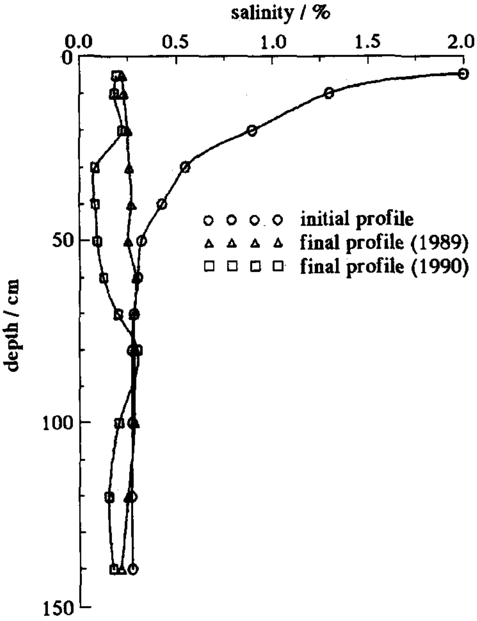

Fig.2 The salinity profiles before and after leaching (1989, 1990)

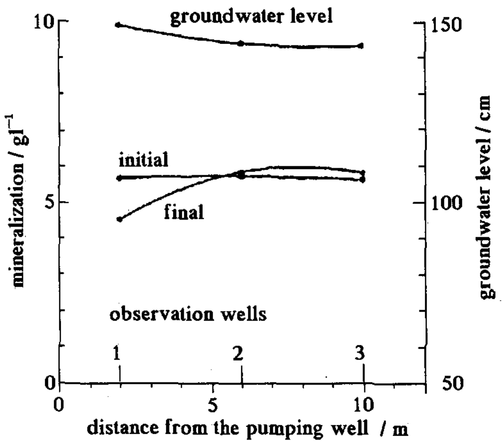

Fig.3 The variation of groundwater level and mineralization in the neighborhood of pumping well

continuous operation in the 1990 test and intermittent one in the 1989 test. Therefore, the continuous irrigation model could save the leaching time but require more quantity of water[2].

3 LABORATORY SIMULATION OF SOIL SALT LEACHING

As mentioned above, in order to study the rapid solonchack reclamation approach systematically , some detailed simulation experiments were performed in a laboratory column of 10 cm diameter. In our work, the desalination process under the flood-irrigation and well-drainage conditions were investigated through the pounding leaching tests in a vertical soil column. The experimental system consists of the soil column, the water feeding-draining units and the conductimetric instrument units. The soil samples were taken from the test field directly. Before the leaching simulation experiments, the soil water movement parameters should be measured since they are needed for the numerical simulation. The soil water potential-water content relationship $h(\theta)$ is shown in Fig.4 and the curve of the soil water diffusivity $D(\theta)$ is plotted in Fig.5. The diffusivity can be easily obtained through a horizontal infiltration method[3]. During the horizontal infiltration process, the soluble salt in the sample soil can be carried away by the infiltration water to one end of the column. As a result, a desired salt distribution was formed similar to the primary salinity profile in the test site.

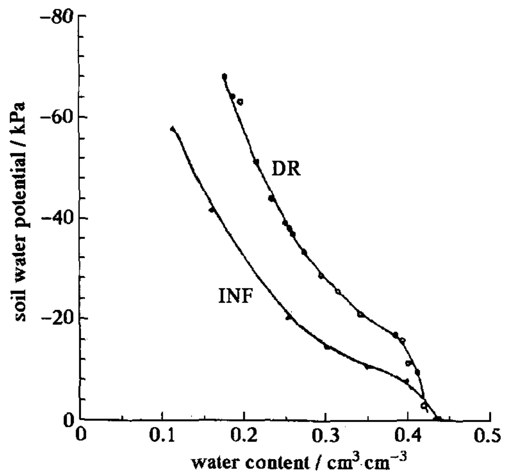

Fig.4 Soil water potential as a function of water content (silt loam, $\rho = 1.43$)

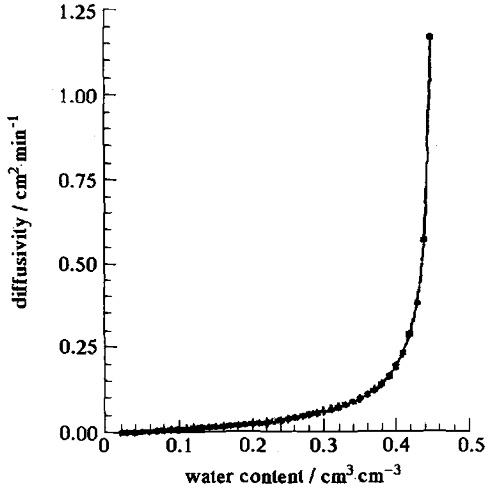

Fig.5 Soil water diffusivity as a function of water content (silt loam, $\rho = 1.43$)

The soil column was set upright when it attained the saturation condition. For the pounding vertical infiltration tests, a water layer over the soil surface was retained to the depth of 4 cm and the water exit kept at the level of the soil bottom. In these experiments, the water infiltration quantity and soil salt concentration were recorded. To determine the salt concentration, 14 salt transducers were inserted into the saturated soil along one side of the column. The salinity profiles along the column at several different moments are given in Fig.6.

4 NUMERICAL SIMULATION OF WATER AND SALT MOVEMENT

The rapid leaching reclamation of saline soil under investigation is a soil water and salt solute transport problem[4~7]. In the present work, the water and salt movement in the leaching process is numerically simulated for both the field and laboratory conditions.

To describe the simultaneous flows of water and salt in soil, the one-dimensional convection-dispersion governing equations in the coordinates of time t and depth z can

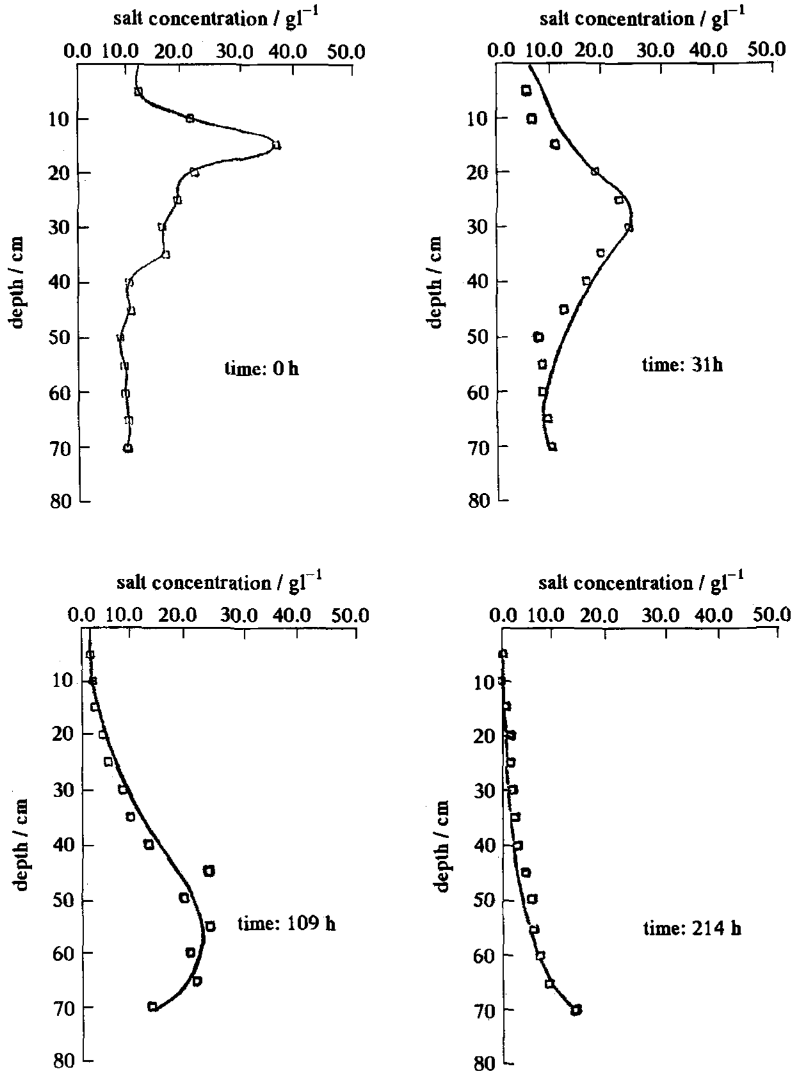

Fig.6 Salt concentration profiles during the pounding leaching of the vertical soil column

—— computational, □ □ □ □ experimental

be expressed as follows:

(1) Hydrodynamic equation for soil water

$$\begin{array}{ll} \tilde{C}(h)\dfrac{\partial h}{\partial t} = \dfrac{\partial}{\partial z}\left[K(h)\dfrac{\partial h}{\partial z}\right] - \dfrac{\partial K(h)}{\partial z} & z \in \Omega \\ h(z,t)|_{t=t_0} = h_0(z) & z \in \Omega \\ h(z,t) = h_1(t) & z \in \Gamma_1 \\ K(h)\left[\dfrac{\partial h}{\partial z} - 1\right] = -q(z,t) & z \in \Gamma_2 \end{array} \qquad (1)$$

where, $\tilde{C}$(1/cm) is the water capacity, h(cm) the water potential, K(cm/h) the hydraulic conductivity and q(cm/h) is the Darcy flux of soil solution. The problem domain and border are denoted by Ω and Γ with $\Gamma_1+\Gamma_2=\Gamma$ and $\Gamma_1\cap\Gamma_2=0$. Here Γ_1 and Γ_2 refer respectively to the borders having the first- and second-type boundary conditions.

(2) Transport equation for soil salt

$$\begin{aligned}
&\frac{\partial}{\partial t}(\theta C)=\frac{\partial}{\partial z}\Big[D(V,\theta)\frac{\partial C}{\partial z}\Big]-\frac{\partial}{\partial z}(qC) && z\in\Omega\\
&C(z,t)|_{t=t_0}=C_0(z) && z\in\Omega\\
&C(z,t)=C_1(t) && z\in L_1\\
&\Big[-D(V,\theta)\frac{\partial C}{\partial z}+qC\Big]=\begin{cases} qC_{\text{top}} & \text{for irrigation}\\ 0 & \text{for evaporation}\end{cases} && z\in L_3\\
&\Big[-D(V,\theta)\frac{\partial C}{\partial z}+qC\Big]=qC_{\text{bottom}} && z\in L_4
\end{aligned}\tag{2}$$

where, C(g/l) is the salt concentration, D(cm^2/h) the dispersion coefficient, θ(cm^3/cm^3) is the volumetric water content and V(cm/h) the average pore velocity of soil solution. Here L refers to the problem border with L_3 and L_4 respectively for the top and bottom surfaces where $L_3+L_4=L_2$, $L_1+L_2=L$, $L_1\cap L_2=0$. Similarly, the first- and second-type boundary conditions are given respectively at L_1 and L_2. Based on the continuity principle, the following dispersion equation can be derived from Eq.(2)

$$\theta\frac{DC}{Dt}=\frac{\partial}{\partial z}\Big(D\frac{\partial C}{\partial z}\Big)\tag{3}$$

Equations (1) and (3) are numerically solved by the finite difference method. For discretization, an implicit scheme is applied to Eq.(1)

$$\begin{aligned}
\tilde{C}_i^{j+1/2}\frac{h_i^{j+1}-h_i^j}{t^{j+1}-t^j}=\frac{1}{z_{i+1/2}-z_{i-1/2}}\Big[&K_{i+1/2}^{j+1/2}\frac{h_{i+1}^{j+1}-h_i^{j+1}}{z_{i+1}-z_i}-\\
&K_{i-1/2}^{j+1/2}\frac{h_i^{j+1}-h_{i-1}^{j+1}}{z_i-z_{i-1}}-\big(K_{i+1/2}^{j+1/2}-K_{i+1/2}^{j+1/2}\big)\Big]
\end{aligned}\tag{4}$$

where $\tilde{C}$ and K are determined through an iteration procedure. Similarly, the difference equation for Eq.(3) is given by

$$\theta_i^{j+1/2}\frac{C_i^{j+1}-\bar{C}_i^j}{t^{j+1}+t^j}=\frac{1}{z_{i+1/2}-z_{i-1/2}}\Big[D_{i+1/2}^{j+1/2}\frac{C_{i+1}^{j+1}-C_i^{j+1}}{z_{i+1}-z_i}-D_{i-1/2}^{j+1/2}\frac{C_i^{j+1}-C_{i-1}^{j+1}}{z_i-z_{i-1}}\Big]\tag{5}$$

where $\bar{C}_i^j$ refers to the convection contribution. From the Lagrangian point of view on the total derivative, the term $\bar{C}_i^j$ at the time t^{j+1} for the point Z_i attributes to the salt concentration C_i^j at the previous time t^j for some upstream point. Just from the point, the fluid particle under consideration comes to the current position z_i.

It is noted that, when solving the hydrodynamic equations, the soil water movement parameters $h(\theta), K(h)$ and $\tilde{C}(h)$ should be determined in advance by using a cubic spline method according to the experimental data in Fig.4 and 5. The salt dispersion coefficient is given by Ref.[8,9]

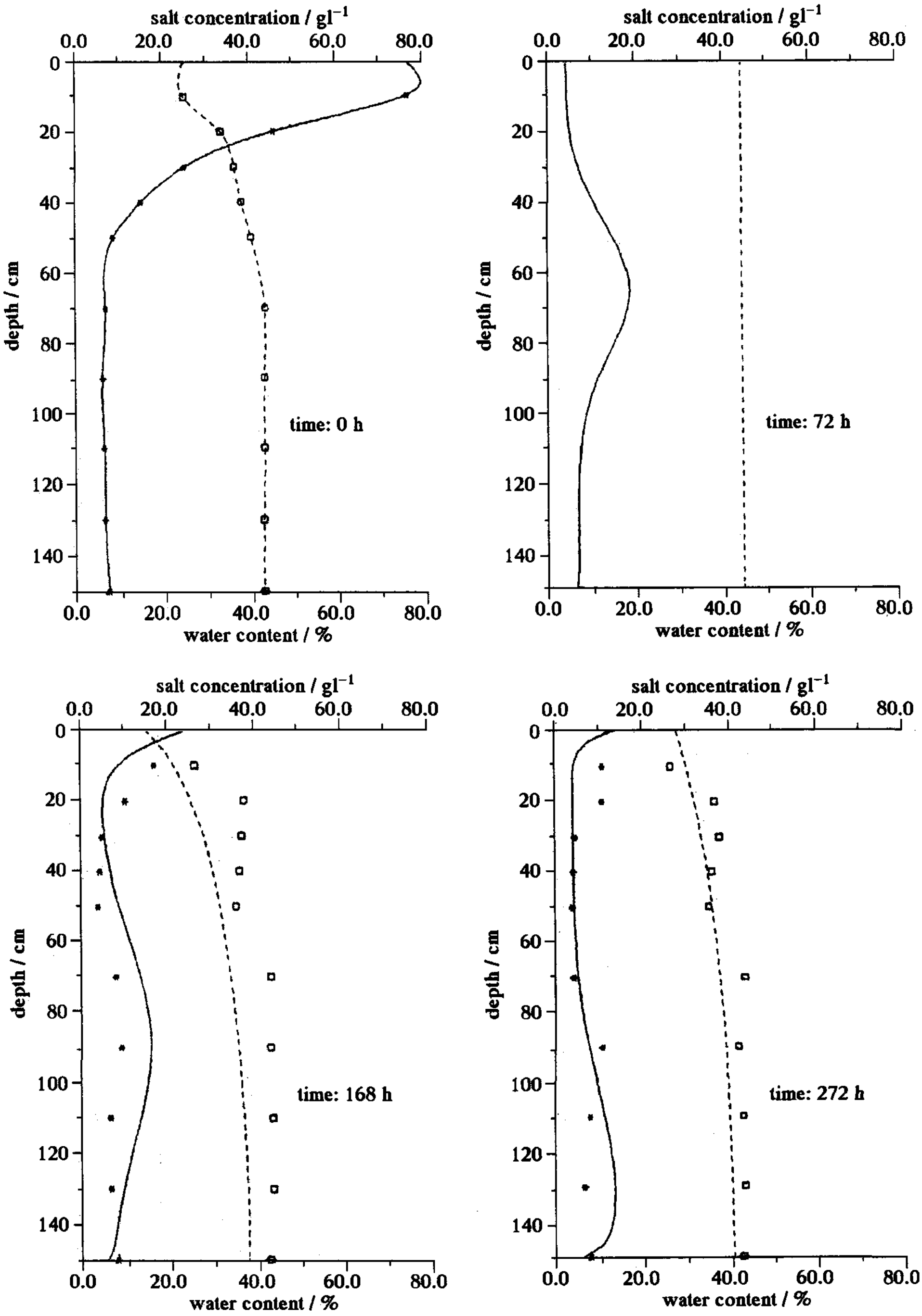

Fig.7 Comparison of computational and experimental profile for the field case

—— computational salt concentration * salt concentration for the field test

– – – computational water content □ water content for the field test

$$D(V,\theta) = \lambda|V| + D_0 a e^{b\theta} \tag{6}$$

where λ[cm] is the dispersivity; D_0 is the molecular diffusion coefficient of salt in a free solution; a and b are the fitting parameters. For the silt loam, $\lambda = 1.0\,\text{cm}$, $a : 0.001 \sim 0.005$ and $b = 10$.

The numerical simulation has been accomplished for the salt leaching tests during a period of about 10 days. Figure 6 shows the numerical results of the pounding infiltration in the vertical column. For these laboratory tests,the salt concentration of the soil column at the initial moment has a similar profile as the field test. Figure 7 shows the numerical results of the intensive irrigation-drainage test at the Beiqiuwa site. In the two figures, corresponding test data are presented for comparison and they indicate a good agreement between the computations and experiments.

It is found from our investigation that before the intensive irrigation-drainage operation, there is a high salt concentration zone in the topsoil due to the original accumulation of salt. When the soil surface is under a pounding saturation condition and the bottom surface is under a drainage condition, this zone is rapidly carried down to the bottom since the pore velocity of soil water increases. Consequently, the accumulation zone extends to a wider range but has a lower peak value. However, when the upper surface is under a dry condition, soil water is evaporated out through its surface. The soil water decreases because of water supply shortage. As a result, the drainage speed at the bottom greatly decreases and then the pore velocity of soil water decreases too. Even the pore velocity can become negative. In this case, the salt accumulation zone does not move down and so some salt diffuses back to the topsoil. Therefore, the flow velocity of soil water is a main factor influencing salt leaching effects.

5 CONCLUSION

In the present study, a comprehensive investigation of the solonchack reclamation by using the flood irrigation and well drainage operation was conducted through three different approaches: field test, laboratory simulation and numerical calculation. The emphasis of the research is placed on the water and salt movement in soil under the intensive irrigation-drainage condition. The obtained results indicate: (1) In the case of shallow groundwater with drainage difficulty, pumping salty groundwater by shallow well is an effective and rapid reclamation method. (2) The leaching effects of the intensive irrigation-drainage operations are in proportion to the water infiltration quantity. (3) Continuous irrigation model can save leaching time, whereas intermittent irrigation model can save infiltration quantity.

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