water

MDPI

Article

Effect of Bypass-Flow on Leaching of Salts in a Cracking Soil in the Nile Delta

Haruyuki Fujimaki * and **Hassan Mohamed Fahmy Abd El Baki**

Arid Land Research Center, Tottori University, Tottori 680-0001, Japan; Hassan.wat2@yahoo.com
* Correspondence: fujimaki@tottori-u.ac.jp; Tel.: +81-857-21-7040; Fax: +81-857-29-6199

Abstract: Salinity is a major threat to the sustainability of irrigated agriculture in arid and semi-arid regions. Leaching is the primary measure for removing excess salts from the root zone, but not all water applied to the soil surface contributes to the removal of salts. In clayey soils, bypass flow along cracks can occur without being mixed with saline pore water in the matrix. To present a field dataset to quantitatively evaluate the contribution of bypass flow to the leaching of salts, soil sampling and monitoring of groundwater and discharge from a tile drain were carried out in farmland having a cracking soil in the Nile Delta. The electrical conductivities of 1:2 extracts were measured to evaluate the salinity of the soil. The first evidence for the occurrence of significant bypass flow through cracks was the salinity of the pore water, which was nearly triple that of the shallow groundwater and outflow from drainage. Second, the difference in root zone salinity before and after paddy rice cultivation was not significant. Third, the gradient of the groundwater table was very small. in spite of the low saturated hydraulic conductivity. Fourth, the salinity of the outflow from the tile drain dropped just after irrigation or rain. These results indicated that bypass flow through cracks played a significant role in the drainage process in the soil, and that nearly half of the water bypasses through cracks in the field with a cracking soil.

Keywords: salinity stress; solute transport; preferential flow; drainage

check for updates

Citation: Fujimaki, H.; Abd El Baki, H.M.F. Effect of Bypass-Flow on Leaching of Salts in a Cracking Soil in the Nile Delta. *Water* **2021**, *13*, 993. https://doi.org/10.3390/w13070993

Academic Editor: Francesco Fiorillo

Received: 5 March 2021
Accepted: 2 April 2021
Published: 4 April 2021

1. Introduction

Since the dawn of civilization, salinity has been a major threat to the sustainability of irrigated agriculture in arid and semi-arid regions. For example, Alexakis et al. [1] assessed the soil salinization in western Greece and found that the soil salinity is mainly controlled by seawater intrusion or other factors such as the application of salt-rich drainage water [2]. To remove excess salts from the root zone to mitigate the salinity hazard, more water than that required to meet crop evapotranspiration is periodically applied [3]. Such an intentional "over-irrigation" is called leaching, which has been the primary measure and widely practiced for salinity control. A guideline for calculating leaching requirements, how much water should be applied for leaching, was presented by Food and Agriculture Organization (FAO) irrigation and drainage paper 29. However, not all water applied to the soil surface contributes to removing salts. In clayey soils, bypass flow along cracks formed with drying and shrinking can occur without being mixed with saline pore water in the matrix. FAO paper 29 recommends breaking cracks by tillage and applying water intermittently to reduce bypass flow. However, no procedure to determine the additional water required to compensate the bypass flow has been presented. Recently, Minhass et al. [4] reviewed recent developments in salinity management studies but did not refer to the matter of bypass flow. The lack of field data and quantitative evaluation of the contribution of bypass flow may account for the inadequate guidelines and undervaluing of this problem. Surface irrigation is still dominant in developing countries, and leaching is usually carried out under continuous ponding [5].

Oster et al. [6] compared three methods of leaching: continuous ponding, intermittent ponding, and sprinkler, and noted that the lower leaching efficiency of continuous ponding is attributable to bypass flow in cracks and macropores. Moreno et al. [7] reported a 10 times larger apparent intake rate for ground with cracks than a matrix in Las Marismas, Spain, and recommended a shorter irrigation interval and lower input each time. Corwin et al. [8] carried out a lysimeter experiment and noted that the effect of bypass flow was small because it occurs only in the top 30 cm, although most water is taken up by the annual irrigated crops from the top 30 cm. Still, there is a lack of field data to quantitatively evaluate how much additional water is needed to attain the target salinity in the root zone.

The objective of this study was, therefore, to present a field dataset from cracking soil in the Nile Delta to quantitatively evaluate the contribution of bypass flow in the leaching of salts.

2. Materials and Methods

The field observation was carried out in an experimental farmland in Sakha (31°05′53.9″ N, 30°55′19.1″ E), Egypt, which was managed by the Agricultural Research Center of Egypt (Figure 1). The field was under a series of cropping experiments to evaluate actual evapotranspiration rates from a surface irrigated field using the eddy correlation method [9]. Cultivated crops and periods are listed in Table 1. All crops were irrigated with surface irrigation. The electrical conductivity of the irrigation water fluctuated between 0.4 and 0.5 dS m^{-1}.

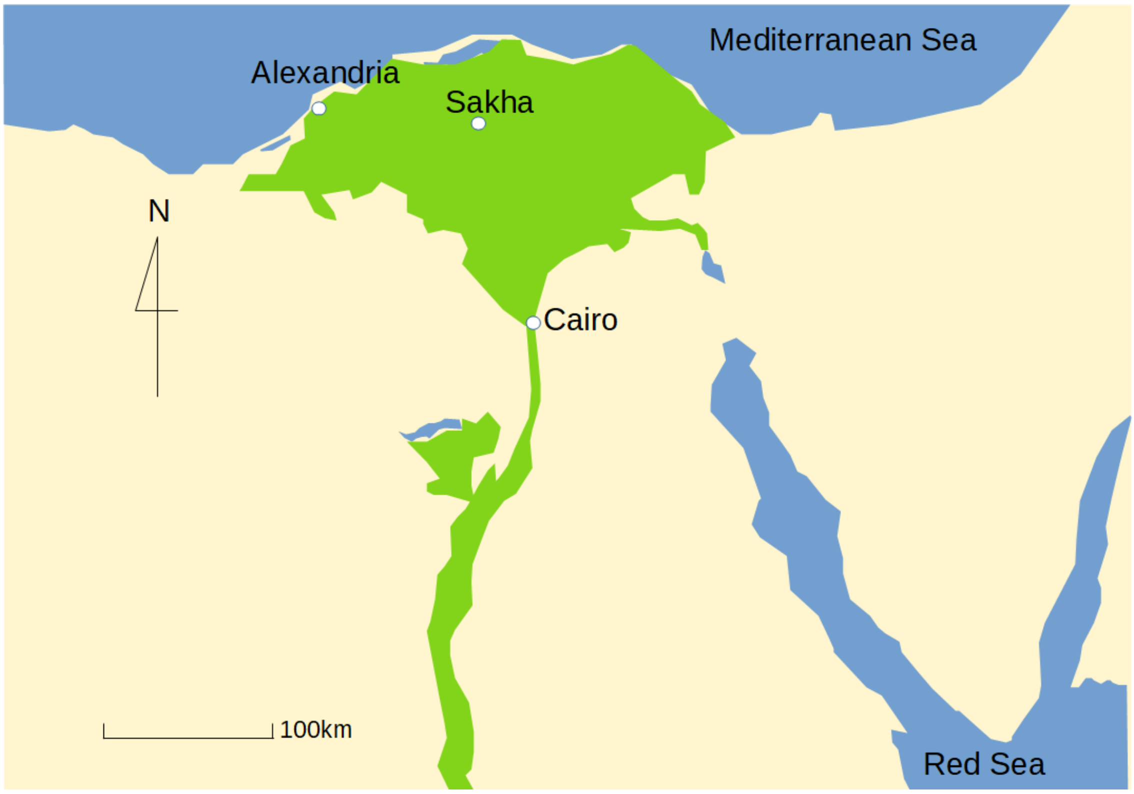

Figure 1. Location of the study site. Area painted green represents farmland and cities.

The farmland had tile drainage pipes, whose inner diameter, depth, and length were approximately 0.072, 1.5, and 50 m, respectively. No envelope material was used for the tile drainage pipes. Nine observation wells were installed to monitor the groundwater level and EC at an equal spacing of 6.25 m along a line perpendicular to the tile drains, as illustrated in Figure 2. Groundwater level was measured using a water level meter (Yamayo, WL10M, Tokyo, Japan).

Table 1. Cultivation record of the farmland.

Period	Crop	Irrigation Method
2011/2012 winter	Wheat	Basin
2012 summer	Rice	Basin
2012/2013 winter	Wheat	Basin
2013 summer	Maize	Furrow
2013/2014 winter	Sugarbeet	Furrow
2014 summer	Rice	Basin

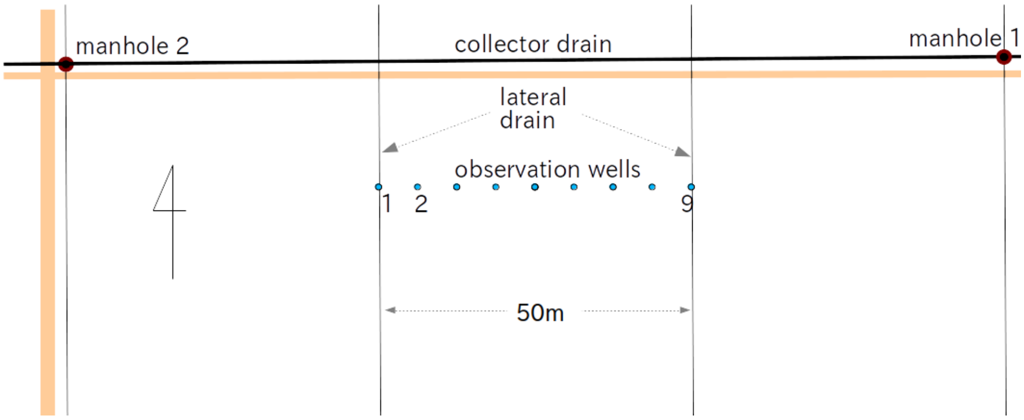

Figure 2. Structure of lateral and collector drains. Monitoring of discharge was carried out in manhole 1. Orange lines represent roads.

On 18 April 2012, 23 April 2014, and 20 October 2014 soil samples were taken to obtain soil salinity profiles. The first sampling was carried out at two randomly selected locations, while the others were taken at certain intervals from the lateral drains.

The electrical conductivity (EC) of (soil-to-water ratio) 1:2 suspension was measured, and pore water EC was calculated using the gravimetrically measured volumetric water content [10]. Assuming no dissolution of low solubility salts nor desorption occurs by dilution, and a linear relationship between concentration and EC, pore water conductivity, σ_{sw} (dS m^{-1}), can be calculated as

$$\sigma_{sw} = \frac{N\rho_b}{\theta\rho_w}\sigma_S \quad (1)$$

where N is the dilution factor (in case of 1:2 method, N = 2), ρ_b is bulk density (Mg m^{-3}), θ is volumetric water content, ρ_w is density of water (Mg m^{-3}), and σ_S is EC of the suspension (dS m^{-1}).

EC was measured with an EC meter (Horiba, B-173, Kyoto, Japan), and calibration using 1 M KCl solution was carried out just before each measurement.

There were manholes for maintenance work at every three lateral tile drainage pipes along the collector drainage pipe. To observe the discharge rate from the lateral pipes, we installed a PVC pipe with 50 cm length and 2.5 cm diameter into a manhole, so that water outflowed or inflowed through the pipe, as illustrated in Figure 3. Pressure in the lateral pipe was measured with a water level sensor (Senses, JW8000-02M, Tokyo, Japan), and water level in the manhole was also monitored. Assuming that head losses at the inlet and outlet were negligible, discharge rate, Q (m/s), was calculated using the Hazen–William Equation [11]:

$$Q = C_H\left[\frac{10.671}{D^{4.87}(h_i - h_o)}\right]^{0.54} \quad (2)$$

where C_H is the Hazen–William coefficient, l is length of the pipe (m), D is diameter (m) of the pipe, h_i and h_o are the pressure head at the inlet and outlet of the pipe (m), respectively. When water level in the manhole was lower than the outlet of the PVC pipe, h_o was set at 0. A value of 130 for C_H of the PVC pipe was used. EC of the discharged water was also monitored using an EC sensor (ES-2, METER, Pullman, WA, USA)

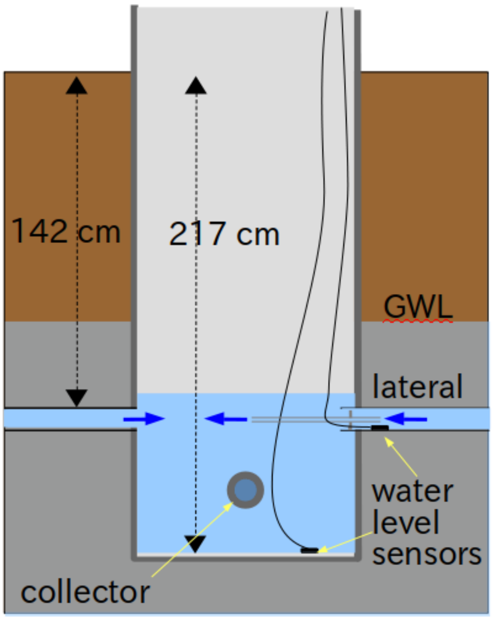

Figure 3. Setup for monitoring discharge rate from the lateral tile drainage pipe.

3. Results and Discussion

3.1. Salinity of Soil Solution

Profiles of soil moisture and salinity under wheat cultivation are shown in Figure 4. Both profiles showed a slightly decreasing EC of the soil solution with depth. The EC of soil solution (pore water EC) was nearly 10 times that of the irrigation water, which implied a low effective leaching fraction, but still lower than the threshold value of yield reduction for wheat [3]. According to FAO 29 [3], the yield of wheat reduces from its potential value if average pore water conductivity is higher than 12 dS m^{-1}, owing to salinity stress.

Rice is widely cultivated in nearly half of farmlands in the summer in the Nile Delta [12,13]. Owing to its large water requirement, the Egyptian government has tried to restrict rice cultivation. However, continuous ponding may have a side effect of the enhancement of leaching salts [13]. Therefore, soil samples before and after rice cultivation were taken in 2014. Figure 5 shows the profiles of pore water EC before transplanting of rice (at the end of sugarbeet cropping).

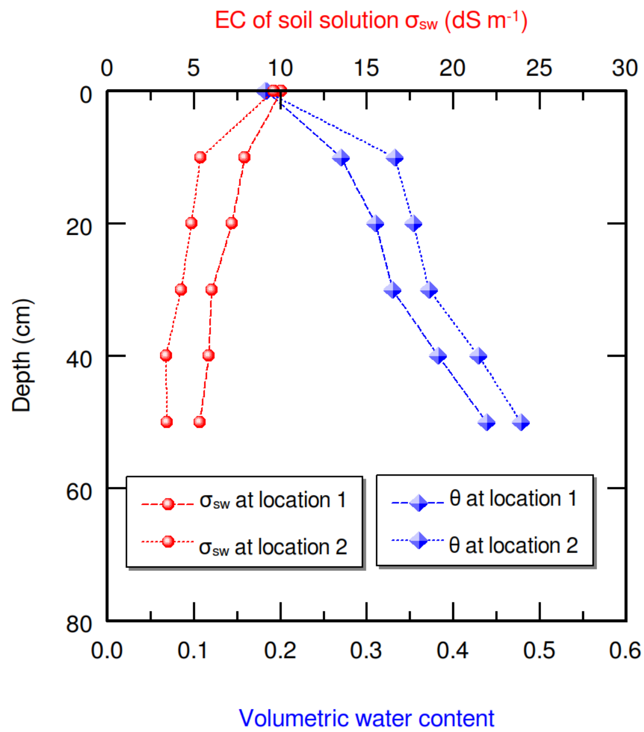

Figure 4. Pores of water content and salinity on 18 April 2012.

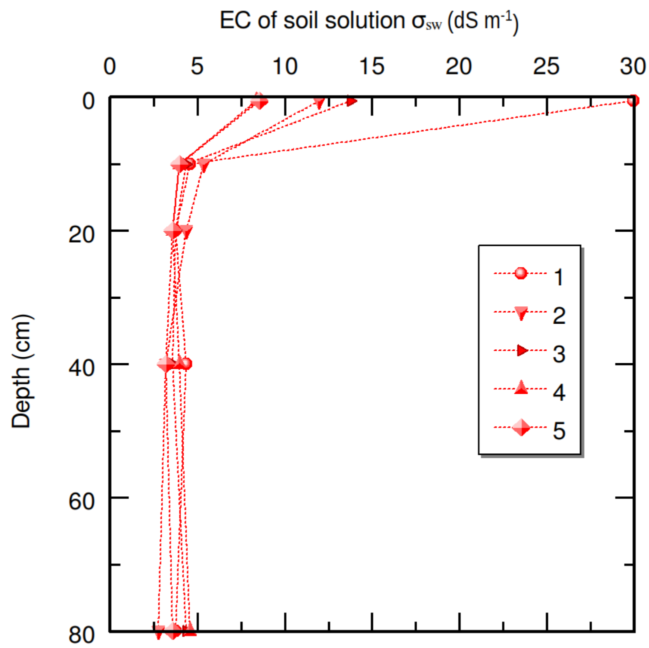

Figure 5. Profiles of pore water salinity at different distances from the lateral under sugar beet cropping (23 April 2014).

To investigate whether there was significant difference in salinity at different distances to the lateral, soil sampling was carried out at five locations, with equal spacing (10 m) between the lateral. The profiles labeled 1 and 5 were taken above the laterals. Except for the soil surface, where salt accumulation driven by evaporation occurred between irrigation, the pore water EC was fairly uniform and close to that of Figure 4. Profiles of the salinity of soil solution after rice cultivation are shown in Figure 6. Since no significant effect of the distance to laterals was found in Figure 5, samplings were carried out at just two locations: above the lateral and intermediate between two.

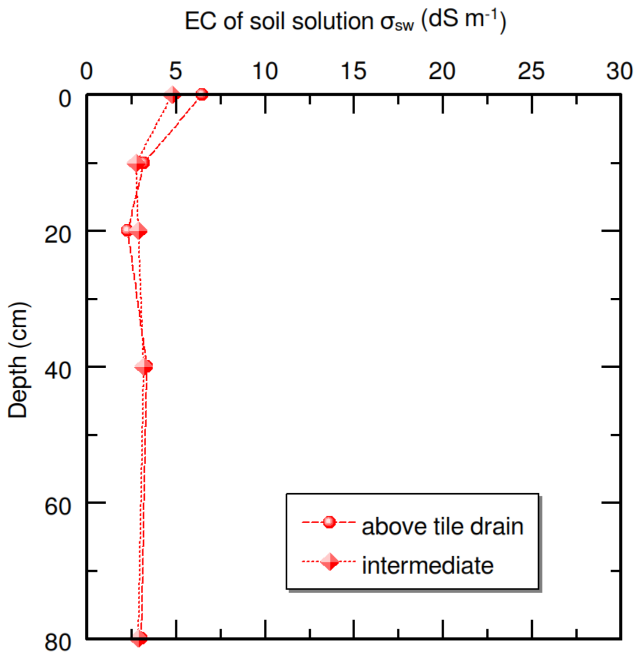

Figure 6. Profiles of pore water salinity at different distances from the lateral after rice cultivation (20 October 2014).

By using the relationship between EC and total dissolved solids, σ_{sw} can be converted to concentration. By integrating the product of volumetric water content and concentration across soil profile, stored salts above a certain depth can be obtained. EC (dS m^{-1}) can be converted to concentration of salts (or "total dissolved solids") (g L^{-1}) by multiplying by a factor of 0.64 [3]. Stored salts above the depth of 80 cm before and after rice cultivation were 64 and 63 mg cm^{-2}, respectively. Even after nearly continuous ponding during rice cultivation, salinity did not significantly decrease. These results indicate that a significant part of the infiltrated water may have bypassed through cracks without flowing into the soil matrix. The soil was characterized by a low saturated hydraulic conductivity (1.4 cm d^{-1} [13]) for disturbed, repacked soil samples, and by swelling-and-shrinking, responding to changes in water content. Kubota et al. (2017) observed a 12% soil depression (i.e., 36% decrease in volume) using a depression gauge, which occurred in the top 20 cm in May 2014 for the soil [13]. Okuda et al. [14] investigated the effect of leaching carried out twice during the winter in Uzbekistan and reported that even after 310 mm of leaching and 127 mm of rain, which may be nearly one pore volume down to 80 cm, 75% of salts remained in top 100 cm. This may also indicate the difficulty of leaching by ponding for fine textured soils.

3.2. Change in Depth and EC of Groundwater

The temporal change in ground water depth is shown in Figure 7. Regardless of distance from the laterals, the ground water level was nearly synchronized and quite uniform. This clearly violates the assumption of homogeneity often used in numerical simulations of water flow and solute transport in soils. The most simplified prediction of the depth of a groundwater table would be Hooghout's steady-state solution [14]:

$$h = h_0 + \sqrt{\frac{q}{K_s}(Sx - x^2)} \quad (3)$$

where h is ground water level (m), q is groundwater recharge rate (m d^{-1}), K_s is saturated hydraulic conductivity (m d^{-1}), S is spacing of the lateral drain (m), x is distance from lateral drain (m), and h_0 is h at x = 0.

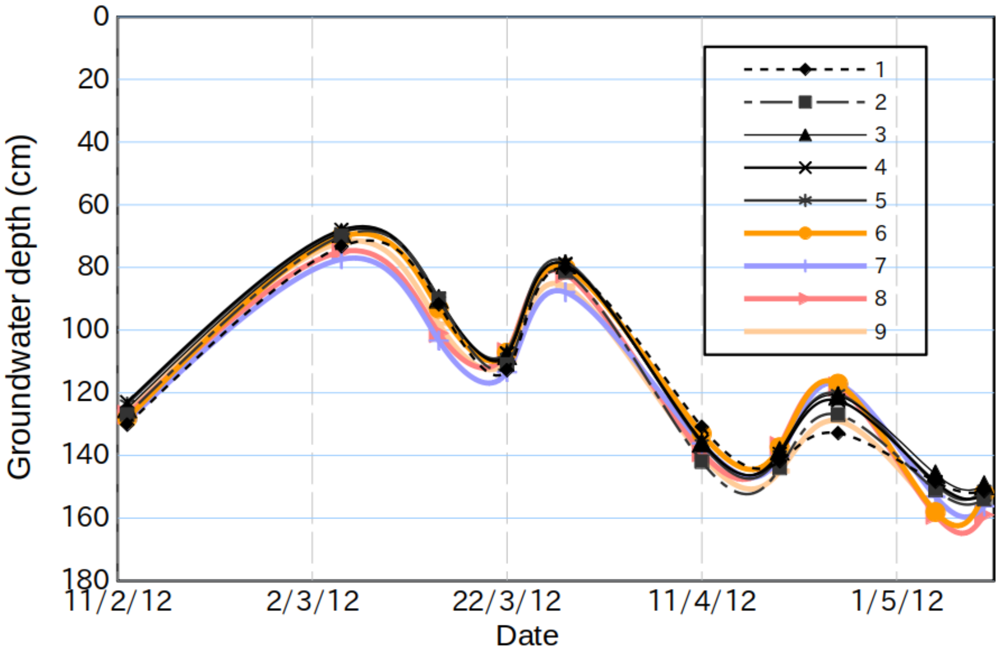

Figure 7. Changes in the groundwater depth.

Figure 8 shows the distribution of groundwater depth calculated using Equation (3) at q = 0.0005 m/d, which is a typical drainage rate under the recommended leaching fraction of 0.15–0.2 [3] and measured K_s. As much as 1 m of difference in ground water depth should occur if the soil were homogeneous, but in reality only a one-tenth difference between the highest and the lowest levels occurred in the field. This large discrepancy is another piece of evidence that bypass flow caused by cracks plays a dominant role in groundwater flow in cracking soils.

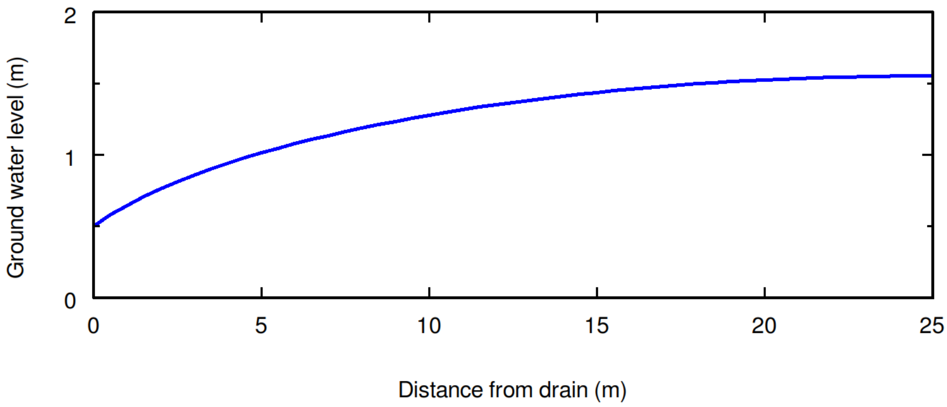

Figure 8. Ground water level calculated by Hooghoudt Equation (q = 0.05 mm d^{-1}, K_s = 1.4 cm d^{-1}).

Changes in the EC of groundwater at each observation well is shown in Figure 9. Except for the EC at No.6 on 12 April, EC values were fairly uniform and stable. The average value on 18 April, when soil sampling was also carried out as shown in Figure 4, was 1.6, which was nearly one-third of that of the pore water. This large difference was also attributable to the dominance of bypass flow.

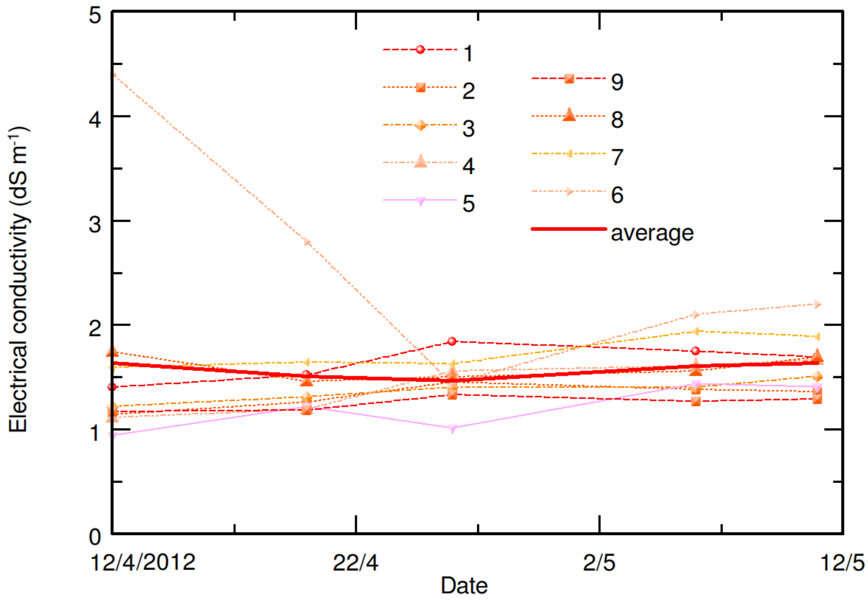

Figure 9. Changes in the EC of groundwater in each observation well.

3.3. Discharge Rate and EC of Outflow from the Lateral Drain

The discharge rate calculated with Equation (2) and divided by the collecting area is shown in Figure 10. Discharge started quickly, just after irrigation. Sometimes inverse flow into the lateral drain occurred because the water level in the manholes often sharply rose, owing to inflow through the collector pipe into the manhole. This complicated motion may have been caused by larger-scale bypass flow and/or non-uniform application of water. Figure 10 also shows the EC of outflow from the lateral drain, which tended to drop immediately after irrigation or rain events and recovered to a steady value of around 1.8. This implies that the bypass flow having low EC came first, followed by flow through the matrix. Zero EC values occurred when water level inside the lateral pipe was lower than the electrode of the sensor.

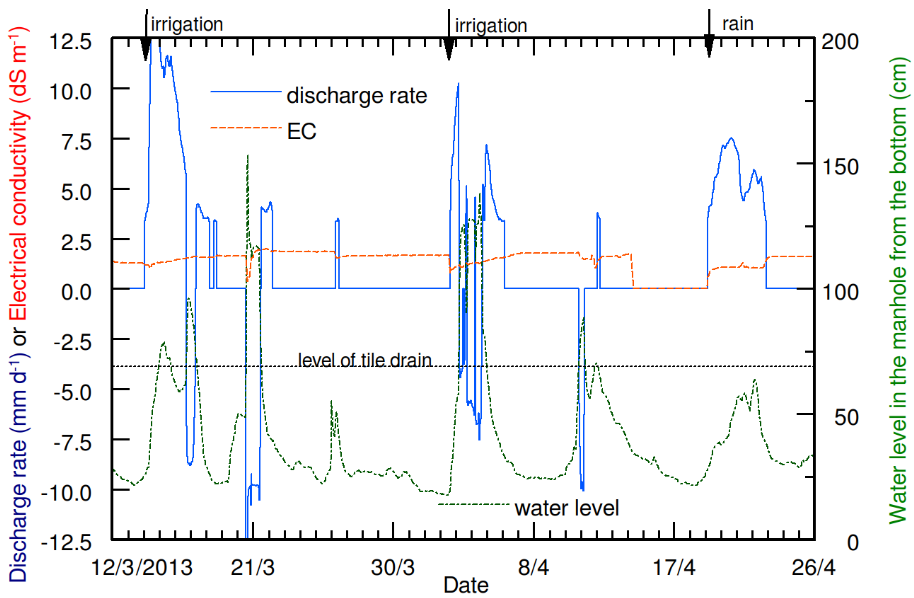

Figure 10. Time variation of discharge rate from the tile drain, EC of discharge, and water level in the manhole.

3.4. Estimation of the Contribution of Bypass Flow

All the results presented above\clearly indicate that bypass flow played a significant role. Although it is difficult to parameterize the contribution of bypass flow in each field, we present a simple way for evaluating the magnitude of the contribution of bypass flow over entire water flow. As depicted in Figure 11, the drainage water or near-surface ground water is a mixture of matrix and bypass flow.

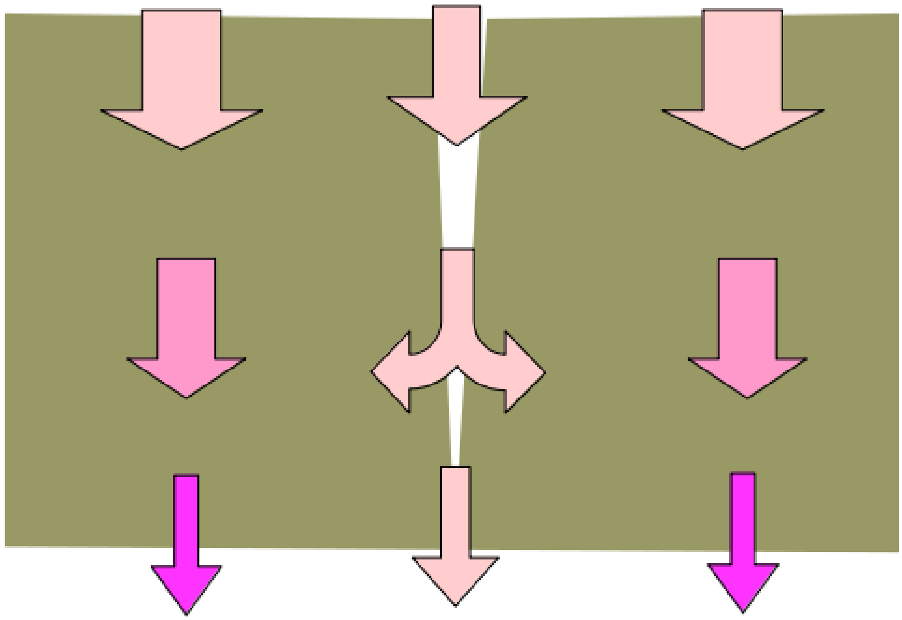

Figure 11. Schematic of the concept of idealized bypass flow which does not receive salts from the matrix.

Thus, assuming that water flowing through cracks does not receive salts in micropores, the total salt load to drainage, $q_d c_d$, would be given as a sum of that through the matrix, $q_s c_s$, and that through bypass flow, $(q_d - q_s)c_i$:

$$q_d c_d = q_s c_s + (q_d - q_s)c_i \tag{4}$$

where q_d is groundwater recharge rate, c_d is the concentration of drainage water, q_s is groundwater recharge rate through matrix, c_s is the concentration of soil water at the bottom of the root zone, and c_i is the concentration of irrigation water. Rearranging Equation (4) gives

$$\frac{q_d - q_s}{q_d} = \frac{c_d - c_s}{c_i - c_s} \approx \frac{\sigma_d - \sigma_s}{\sigma_i - \sigma_s} \tag{5}$$

where σ is electrical conductivity, and subscripts are the same as c. Substituting the values of σ_d = 1.8, σ_i = 0.45, and σ_s = 3.5 into Equation (5) gives a value of 0.55 as the contribution factor of bypass flow. We may state that nearly half of water bypasses through cracks in the field with a cracking soil. In other words, nearly double the water is required to meet leaching requirements.

3.5. Reducing Bypass Flow

As instructed in FAO 29, breaking cracks by tillage and applying water intermittently may reduce bypass flow. Surge flow irrigation may be regarded as a technique for intermittent ponding [15]. Sprinkler and drip irrigation methods may completely prevent bypass flow if irrigation intensity is restricted below the intake rate of the soil. To evaluate the effectiveness of these measures, leaching efficiency should be defined. As leaching is not necessarily carried out as a single event, and rather, frequently carried out under modern and precise management schemes, it is not easy to define leaching efficiency. Still, we would suggest the following equation for leaching efficiency, e_L:

$$e_L = \frac{1}{t} \int \frac{Ec_i}{q_i c_c} dt \quad (6)$$

where E is evapotranspiration rate (m d^{-1}), c_c is the concentration of the most critical location in the root zone, and q_i is irrigation intensity (m d^{-1}). If q_i and c_c were the same as c_i and E, respectively, e_L would be unity (100%), which is theoretically impossible in reality. Still, by minimizing bypass flow, we may enhance e_L, just as we should do our best to maximize application efficiency and irrigation uniformity, although attaining 100% is physically impossible. Recent advances in soil moisture and salinity probes have enabled such evaluations.

4. Conclusions

The nearly triple EC of pore water compared to shallow groundwater and outflow from drainage, the non-significant difference in root zone salinity before and after paddy rice cultivation, the too-small gradient of the groundwater table for its saturated hydraulic conductivity, and the drop in the EC of outflow from the tile drain just after irrigation or rain indicate that bypass flow through cracks played a significant role in the drainage process in a cracking soil in the Nile Delta. A simple analysis indicated that nearly half of the water bypasses through cracks in a field with cracking soil. Further studies to evaluate the leaching efficiency of various methods under cracking soil are required.

Author Contributions: Conceptualization, H.F.; methodology, H.F. and H.M.F.A.E.B.; validation, H.F. writing—original draft preparation, H.F.; writing—review and editing, H.M.F.A.E.B.; All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Japan International Cooperation Agency and Japan Society for the Promotion of Science [grant name SATREPS "Sustainable Systems for Food and Bio-energy Production with Water saving Irrigation in the Egyptian Nile Basin"].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are openly available in [http://www.alrc.tottori-u.ac.jp/fujimaki/data/egypt/drainage].

Acknowledgments: The authors are grateful to S. Yoshida (University of Tokyo) for providing us the shrinkage characteristic of the soil; Y. Kitamura for his advices for methodology of monitoring; Waleed Abou El Hassan (FAO) for his support in the field monitoring. Finally, the authors also express their deep appreciation to M. Satoh (University of Tsukuba) for his leadership in the project.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Alexakis, D.; Gotsis, D.; Giakoumakis, S. Evaluation of soil salinization in a Mediterranean site (Agoulinitsa district—West Greece). *Arab J. Geosci.* **2015**, *8*, 1373–1383. [CrossRef]
2. Alexakis, D.; Gotsis, D.; Giakoumakis, S. Assessment of drainage water quality in preand post-irrigation seasons for supplemental irrigation use. *Environ. Monit. Assess.* **2012**, *184*, 5051–5063. [CrossRef] [PubMed]
3. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture*; Paper No. 29; FAO Irrigation and Drainage: Rome, Italy, 1985; Available online: http://www.fao.org/3/T0234E/T0234E00.htm (accessed on 3 April 2021).
4. Minhas, P.S.; Ramos, T.B.; Ben-Gal, A.; Pereira, L.S. Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues. *Agric. Water Manag.* **2020**, *227*, 105832. [CrossRef]
5. Okuda, Y.; Onishi, J.; Shirokova, Y.; Kitagawa, I.; Kitamura, Y.; Fujimaki, H. Water and salt balance in agricultural lands under leaching with shallow subsurface drainage used in combination with cut-drains. *Water* **2020**, *12*, 3207. [CrossRef]
6. Oster, J.D.; Willardson, L.S.; Hoffman, G.J. Sprinkling and Ponding Techniques for Reclaiming Saline Soils. *Trans. ASAE* **1972**, *15*, 1115–1117. [CrossRef]

7. Moreno, F.; Cabrera, F.; Andreu, L.; Vaz, R.; Martin-Aranda, J.; Vachaud, J. Water movement and salt leaching in drained and irrigated marsh soils of southwest Spain. *Agric. Water Manag.* **1995**, *27*, 25–44. [CrossRef]
8. Corwin, D.L.; Rhoades, J.D.; Šimůnek, J. Leaching requirement for soil salinity control: Steady-state versus transient models. *Agric. Water Manag.* **2007**, *90*, 165–180. [CrossRef]
9. Sugita, M.; Matsuno, A.; El-Kilani, R.M.M.; Fattah, A.A.; Mahmoud, M.A. Crop evapotranspiration in the Nile Delta under different irrigation methods. *Hydrol. Sci. J.* **2017**. [CrossRef]
10. Sonneveld, C.; Van den Ende, J.; De Bes, S. Estimating the chemical compositions of soil solutions by obtaining saturation extracts or specific 1:2 by volume extracts. *Plant Soil* **1990**, *122*, 169–175. [CrossRef]
11. Mays, L.W. *Hydraulic Design Handbook*; McGraw Hill: New York, NY, USA, 1999.
12. El-Hassan, W.H.A.; El-Kassar, G.; Fujimaki, H.; Kitamura, Y.; Khater, A. Assessment of cost-effective alternatives for improving irrigation Systems in the Nile Delta. *Irrig. Drain.* **2015**. [CrossRef]
13. Kubota, A.; Zayed, B.; Fujimaki, H.; Higashi, T.; Yoshida, S.; Mahmoud, M.M.A.; Kitamura, Y.; Abou El Hassan, W.H. *Water and Salt Movement in Soils of the Nile Delta. Irrigated Agriculture in Egypt*, 1st ed.; Satoh, M., Aboulroos, S., Eds.; Springer: Cham, Switzerland, 2017; pp. 153–186. [CrossRef]
14. Hillel, D.D. *Environmental Soil Physics*; Academic Press: San Diego, CA, USA, 1998.
15. Onishi, J.; Ikeura, H.; Paluashova, G.K.; Shirokova, Y.; Kitamura, Y.; Fujimaki, H. Suitable inflow rate and furrow length for simplified surge flow irrigation. *Paddy Water Environ.* **2019**, *17*, 185–193. [CrossRef]