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Effects of Subsurface Pipe Drainage Spacing on Soil Salinity Movement in Jiangsu Coastal Reclamation Area

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Abstract: The agricultural development of reclaimed coastal areas in Jiangsu Province is significantly hindered by high soil salinity and an inadequate irrigation and drainage infrastructure. Optimizing the layout of subsurface drainage systems has been identified as an effective means of reducing soil salinity, with the proper designation of engineering parameters being crucial. This study applied 12 treatments (T1–T12) consisting of four different spacings of subsurface drainage pipes (6 m, 11 m, 15 m, and no subsurface drainage pipes) and three observation wells at varying distances from the drainage outlet (5 m, 25 m, and 45 m). Results showed that all three subsurface pipe spacing treatments significantly reduced soil salinity compared to natural drainage, with a smaller subsurface pipe spacing treatment leading to better salt-reducing effects. The farther the distance from the measuring point to the drain, the higher the salinity. As the burial depth of the outlet decreased and spacing between the subsurface drainage pipes decreased, the salinization rate of the 0–60 cm soil layer was higher, while the salt accumulation in the 60–80 cm soil layer was more severe. Therefore, a subsurface drainage pipe spacing of 6 m and an outlet burial depth of 40 cm are recommended as more suitable choices to effectively control salt concentration in the soil. The research aimed to provide scientific reference data and technical support for the optimized design of subsurface drainage engineering parameters while promoting efficient desalination of saline-alkali areas worldwide.

Keywords: sustainable agriculture; soil amelioration; subsurface drainage; desalination technology; engineering parameter; optimal design

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1. Introduction

Food security remains a critical global issue that needs to be solved. According to the latest report by the Food and Agriculture Organization of the United Nations (FAO), more than 820 million people worldwide are threatened by hunger and malnutrition [1]. While China has achieved relatively stable growth in overall food production, it still faces challenges such as shortages of land and water resources and structural reforms in agricultural supply. With the acceleration of urbanization and industrialization, agricultural resources in China are being occupied, and the country's environmental and resource conditions for agricultural production are facing severe challenges. Therefore, efficiently utilizing undeveloped land resources to cope with the growing population and demand for food is of crucial importance. China has vast potential for developing and utilizing approximately 99 million hectares of saline-alkali land, which is considered an important reserve land resource. Among them, coastal saline-alkali soil accounts for about 7% of the total saline-alkali land area [2]. Currently, there are 230,000 hectares of comprehensively improved saline-alkali soil used for cultivation in China, resulting in an annual increase of more than 20 billion kilograms of grain, cotton, and oilseed production. This indicates that through scientific and reasonable improvement of saline-alkali land, the yield and planting area of agricultural products can be greatly increased, making important contributions to the national economy and agricultural development. Therefore, solving the food security issue requires the rational use of existing land resources, particularly in coastal saline-alkali areas where governance and utilization of saline-alkali land should be strengthened to improve its food production capacity.

There are several methods for improving saline-alkali land, including biological, chemical, physical, and hydraulic improvements [3–6]. Among them, hydraulic improvement is the most common and efficient method, which improves water conditions to increase precipitation utilization efficiency and alleviate salinization. Artificial drainage, construction of irrigation facilities, afforestation, and other methods can be used for hydraulic improvement [7–10]. Subsurface drainage is a commonly used technology in hydraulic improvement, which uses underground pipelines to remove excess water from saline soil. This technology can control groundwater levels, regulate soil moisture, improve physical and chemical soil properties, and effectively improve saline-alkali land [11]. Moreover, compared with traditional drainage methods, subsurface drainage has many advantages, such as strong drought resistance, high planting density, good economic benefits, and improved soil quality, which can better reduce soil salinity [12,13]. Some studies have shown that by studying the effects of different drainage depths, drainage spacing, and pipeline diameters on soil salinity, appropriate layout parameters of subsurface drainage pipelines can be determined, thereby reducing soil salinity and achieving the purpose of saline-alkali land management [14,15]. A shallower burial depth of subsurface pipes allows for the quicker discharge of infiltrated water, resulting in an increased downward infiltration rate of water above the subsurface pipes due to gravity. Moreover, when the subsurface pipes are buried at a shallower depth with the same amount of irrigation, the soil layer above the pipes becomes thinner. This leads to less water retention by the soil above the pipes and more efficient water discharge through the pipes [16]. Reducing the drainage spacing creates a denser drainage network, enabling a more uniform distribution of the drainage system throughout the soil. This helps to minimize the uneven distribution of salt in the soil, preventing the accumulation of salt in specific areas and facilitating balanced removal of soil salt [17]. A larger pipe diameter provides a bigger conduit, allowing for the rapid discharge of a larger volume of drainage water. This aids in the prompt removal of salt, reducing its residence time and preventing its accumulation in the soil [18]. However, to further enhance the application effect of subsurface drainage technology, it is necessary to strengthen the research and formulation of standards and formulate corresponding technical standards and layout patterns based on different geographical and soil conditions to promote innovation and the application of technology [19–22]. One of the main reasons for the unsatisfactory performance of this method is the lack of standardization in the layout pattern of subsurface drainage technology. For instance, parameters such as subsurface drainage spacing still require further research [23–25]. The selection of the layout pattern also faces challenges, such as how to choose subsurface drainage pipe spacing when the control outlet depth is constant, or how to choose the control outlet depth when the spacing is constant.

The soil in the reclamation area along the coast of Jiangsu Province has high salt content and groundwater mineralization with high soil sand content, low terrain, and a high groundwater level [26]. These conditions make crops vulnerable to salt, alkali, and waterlogging. Additionally, the lack of a well-developed irrigation and drainage infrastructure is a significant factor in the restriction of agricultural development in this region. In order to break these constraints and achieve standardized and large-scale construction, direct norms cannot be applied, conventional technologies cannot be borrowed directly, and practical experience is lacking. Therefore, it is necessary to explore the optimal layout pattern of subsurface drainage and study the impact of its drainage and desalination efficiency. The main purpose of this study is to obtain a better layout pattern for subsurface drainage through research on different subsurface drainage spacing treatments, the distance between observation wells and drainage outlets, and control measures for subsurface drainage. This will enable the quick and effective reduction of soil salinity and provide technical support for the desalination of saline-alkali land in the coastal areas of Jiangsu.

2. Materials and Methods

2.1. Study Area

The experimental area is situated in Jianggang Town, Dongtai City, Jiangsu Province (32°51′44″ N, 120°53′47″ E), as shown in Figure 1. It falls within a typical monsoon climate zone with an average annual temperature of 14.7 °C [27]. The average annual precipitation in the area is 980–1100 mm, with uneven distribution of rainfall. Particularly during the rainy season from June to September, rainfall accounts for 40–60% of the total annual precipitation. The dry season experiences less rainfall and stronger evaporation, with a yearly evaporation rate of approximately 1200 mm, slightly exceeding the annual rainfall [27]. The topography in this area is low-lying, and the groundwater depth is shallow. The depth of the groundwater varies across seasons with a depth of 0.2–0.5 m in summer, about 1.0 m in spring and autumn, and 1.5–2.5 m in winter. The soil in the experimental area is mainly composed of coastal sandy soil, with a soil bulk density ranging from 1.40 to 1.52. Due to the comprehensive effects of factors such as the groundwater level, precipitation, layout of irrigation and drainage canals, season, and evaporation, the distribution of soil salinity is uneven. Local data indicates that the lowest and highest soil salinity levels are 0.5 g/kg and 23 g/kg, respectively, with a generally high soil salinity level classified as heavy salt soils or even extremely heavy salt soils (Table 1) [28]. The majority of unimproved land in the experimental area has salt deposits on the soil surface with salt return occurring even after artificial improvement. The basic soil parameters of the total study area in this study are presented in Table 2, and the Simple of Number 3 and Number 4 are in the experimental area. The initial salt ion content of the experimental area soil is displayed in Table 3, the testing methods for soil indicators refer to soil chemical analysis [29].

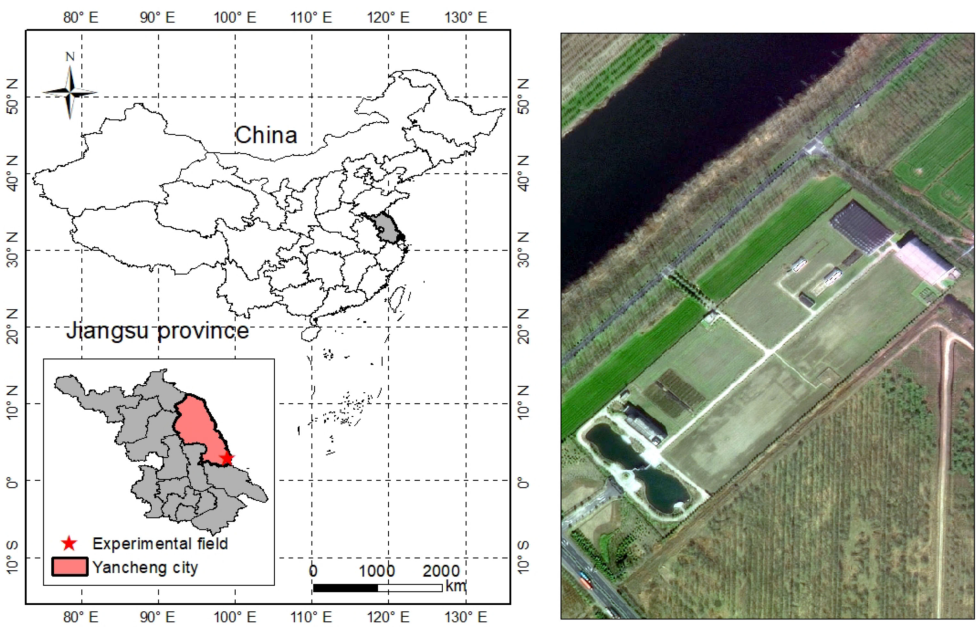

Figure 1. Geographical location of the study area.

Table 1. The classification criteria for saline-alkali land.

Classification	Salt Content (g/kg)	Alkali Content (g/kg)
Slight Saline-alkali	<2	<3
Moderate Saline-alkali	2–5	3–8
Severe Saline-alkali	5–10	8–15
Very Severe Saline-alkali	>10	>15

This table is cited from [28].

Table 2. Basic soil parameters in the study area.

Sample Number	Water Content (%)	Soil Bulk Density (g/cm^3)	Electric Conductivity (μs/cm)	Total Salt Content (g/kg)	Organic Matter (g/kg)	Mechanical Composition (%)				
						>0.05	0.05~0.01	0.01~0.005	0.005~0.001	<0.001
1	25.9	1.46	0.438×10^4	11.19	1.64	34.8	50.2	8.8	1.2	5.0
2	26.2	1.44	0.548×10^4	14.01	2.22	27.4	55.2	9.2	1.8	6.4
3	27.4	1.52	0.166×10^4	4.22	1.15	35.6	53.8	4.6	0.8	5.2
4	30.5	1.39	0.153×10^4	3.99	1.26	43.4	47.4	2.4	2.4	4.4

Table 3. Soil initial salt ion content in the study area (g/kg).

Depth (cm)	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	$SO_4{}^{2-}$	$HCO_3{}^-$
0~20	3.581	0.335	0.228	0.402	0.987	0.321	0.057
20~40	3.485	0.204	0.145	0.125	1.125	0.258	0.042
40~60	3.468	0.185	0.165	0.167	2.254	0.452	0.051
60~80	3.402	0.214	0.158	0.148	3.154	0.345	0.061

2.2. Experiment Design

This experiment utilized field experimentation, with the basic layout of the test field depicted in Figure 2. This study involved a total of 12 treatments (Table 4), including four different spacings of subsurface drainage pipes (6 m, 11 m, 15 m, and no subsurface drainage pipes) and three different distances between observation wells and drainage pipes (5 m, 25 m, and 45 m). The soil salinity sensor was utilized to collect the salinity data of the diverse soil layers at each measurement point in order to obtain the experimental results. Table 3 displays the specific layout of each experimental area. There were 12 measurement points marked as T1–T12, with four soil salinity sensors (FJA-10) buried at 10 cm, 30 cm, 50 cm, and 70 cm below the surface at each measurement point. The measurement points were located near the observation wells utilized to observe the groundwater level at various depths (0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm). The sensors directly measured the conductivity of the soluble salt ions present in the soil solution, and the electrode was stable and highly sensitive, making it ideal for measuring soil salinity.

There were four test areas arranged in a west-to-east direction, namely the control check (CK), A, B, and C. Each test area measured 50 m in length from east to west and approximately 50 m in length from north to south (Figure 2). Isolation zones were positioned outside the control check and Zone C, while field ridges were situated between the isolation zone and the test areas, as well as between the test areas. An underground layer of PE filter material with a thickness of 0.25 mm and a depth of 1.8 m was vertically installed to prevent soil moisture from flowing between the test areas.

Table 4. Different treatment methods for various measurement points.

Measurement Point Number	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Distances between observation wells and drainage outlets (m)	45	25	5	45	25	5	45	25	5	45	25	5
Subsurface drainage pipe spacing (m)	15	15	15	11	11	11	6	6	6	0	0	0

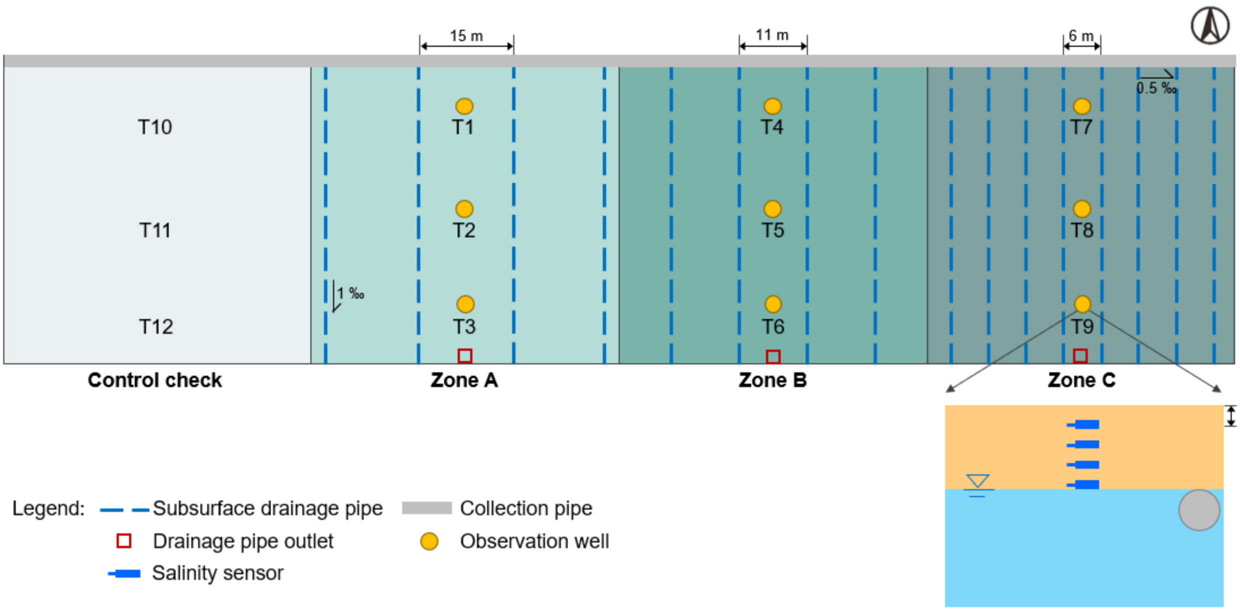

Figure 2. Layout plan of the test site.

The underground drainage system had a two-stage pipe network layout consisting of converging water absorption and water collection pipes. The water absorption pipes and the water collection pipes were interconnected orthogonally and all made of PVC single-wall corrugated pipes. The inner diameter of the suction pipe was 50 mm and the inner diameter of the collecting pipe was set to 90 mm, based on the convergence. The buried depth of both pipes was 0.8 m and the ratio of the suction pipe was 1‰, while the ratio of the collecting pipe was 0.5‰. The collecting pipe entered the end of the sump and was equipped with a valve for drainage control. The drainage control measures are illustrated in Figure 3.

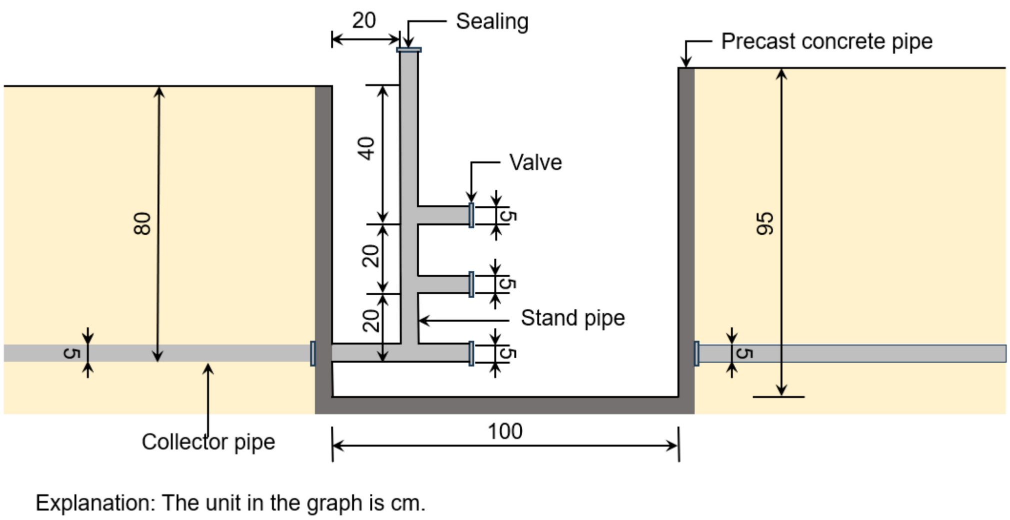

Figure 3. Control drainage facilities profile.

2.2.1. Subsurface Drainage Pipe Spacing

To investigate the effects of different subsurface drainage pipe spacings on soil salinity movement under the same burial depth condition, the changes in soil salinity were assessed at measurement points T2, T5, T8, and T11, located 25 m from the drainage outlet. Soil salinity was measured by soil salinity sensors, with measurements taken once per week. In the event of heavy rainfall, additional measurements were conducted one day prior to and after the conclusion of the rainfall, when the groundwater level receded to 80 cm below the surface.

2.2.2. Distance between Observation Well and Drainage Outlet

To examine the changes in soil salinity under subsurface drainage pipes arranged in the same direction under identical subsurface drainage pipe conditions, soil salinity data were analyzed for the three measurement points (T4, T5, and T6) in Zone B of the experiment using a subsurface drainage pipe spacing of 11 m.

2.2.3. Buried Depth of Subsurface Pipe Outlet

To investigate the regulatory impact of leaching on soil salinity in different soil layers under various drainage control treatments, a comparison of soil salinity levels before and after irrigation was conducted for each layer under different subsurface drainage pipe spacing and control drainage outlet burial depth conditions. During this experiment, three rounds of 75 mm irrigation were applied to the drainage treatment areas spanning 6 m, 11 m, and 15 m, respectively. To assess the effects of different subsurface drainage pipe spacings and drainage outlet burial depths (40 cm, 60 cm, and 80 cm) on soil salinity, combinations of distinct subsurface drainage pipe spacing with identical drainage outlet burial depth and varying drainage outlet burial depths with consistent subsurface drainage pipe spacing were analyzed [19,30,31].

2.2.4. Crop Yield

Sesbania were planted in experimental Zones A, B, C, and D from 30 May 2022 to 30 October 2022. *Sesbania* is an annual herbaceous plant that belongs to the legume family and has a strong resistance to adversity. It is characterized by salt tolerance, waterlogging tolerance, and barren soil tolerance. Under normal circumstances, a total salt content of around 5 g/kg in the cultivated layer of soil is sufficient for seedlings to emerge, although growth is relatively slow. Optimal growth can be achieved with a total salt content of 3 g/kg, while growth is suppressed when total salt exceeds 5 g/kg. The emergence and growth of *Sesbania* are also significantly influenced by different types of saline-alkali soils. Seedlings can emerge and grow in sulfate-dominated saline soils when the total salt content of the surface layer (0–10 cm) reaches 6 g/kg. In chloride-dominated saline soils, seedling emergence and growth are affected when the surface (0–10 cm) total salt content reaches 4 g/kg. In carbonate-dominated alkaline soils, seedlings cannot emerge when the total salt content of the surface layer (0–10 cm) reaches 3 g/kg [32–35].

Soil samples from the surface layer (0–20 cm) were taken for soil salinity analysis. The samples were obtained using a soil auger at three points in each location, using a multi-point mixed sampling method. Samples were mixed from three points at the same depth to ensure that the quality of the mixed soil sample was more than 1 kg. After the mature *Sesbania* was harvested by farmers using a specialized harvester and divided by region, its total weight was measured after being sun-dried.

2.3. Desalination Rate

The desalination rate used to measure the degree of salt content change in different soil layers before and after leaching was calculated using the following equation:

$$m' = (S_1 - S_2)/S_2 \times 100\%$$

where m' is the desalination rate, %; S_1 is the soil salinity level before leaching, g/kg; S_2 is the soil salinity level after leaching, g/kg.

2.4. Statistical Analysis

A one-way analysis of variance (ANOVA) was used to evaluate the effects of subsurface drainage pipe spacing on the yield of a salt-tolerant crop. A *t*-test was used to detect the differences of all treatments ($p < 0.05$). Data were analyzed with the SPSS 25.0 software package.

3. Results

3.1. Effects of Subsurface Drainage Pipe Spacing on Soil Salinity

The dynamic fluctuations in soil salinity levels are depicted in Figure 4.

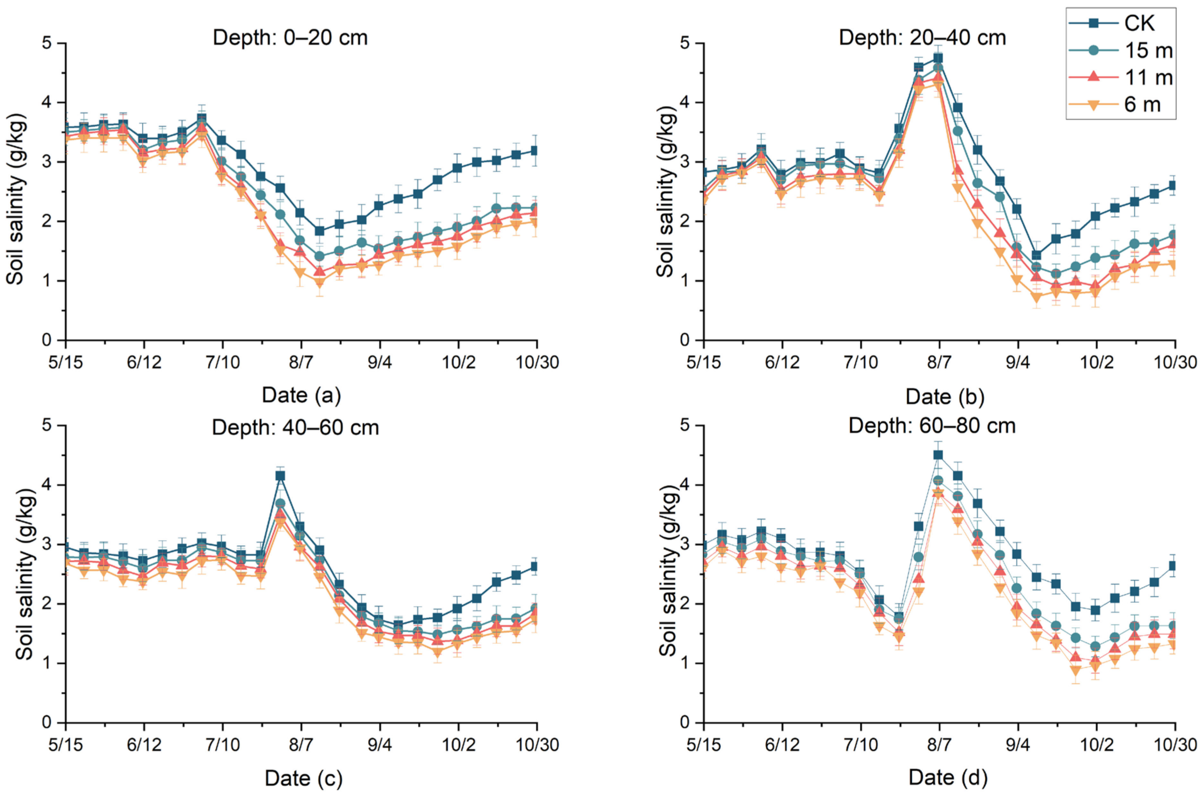

Figure 4. The variation of soil salinity content under different experimental treatments with a longitudinal distance of 25 m.

Previous research findings indicate that precipitation has an impact on leaching and desalination of soil [36]. This study investigated the monthly precipitation in the study area during the experimental period (Figure 5) and analyzed the impact of temporal variability of precipitation on soil salinity movement. It is apparent that from late May to July, soil salinity levels for all four treatments exhibited a substantial decline within the 0–20 cm soil layer (Figure 4a), while salinity levels in the deeper 20–80 cm layers remained relatively stable (Figure 4b–d). Furthermore, the differences in soil salinity levels among the three distinct subsurface drainage pipe spacing treatments were relatively minor. The results of the experiment demonstrate that in August, significant rainfall caused a decline in soil salinity within the 0–20 cm layer but a rise in salinity in the 20–80 cm layer since the salt was carried down into the deeper layers or groundwater. This resulted in a substantial reduction in surface soil salinity, which agrees with previous research [37–39]. In September and October, with a decrease in precipitation, soil salinity levels in the 0–20 cm soil layer increased once again, which resulted in surface salt accumulation.

Moreover, Figure 4 illustrates that after the control check, which was lacking subsurface drainage pipes, the salt content reverted to its initial level. Meanwhile, the other three subsurface drainage pipe treatments featuring distinctive spacing all displayed a significant reduction in salt content and the soil salinity levels in all layers averaged around 2 g/kg, indicating mild soil salinization. The order of soil salinity levels from high to low was natural drainage > 15 m > 11 m > 6 m, which implies that the smaller the spacing between subsurface drainage pipes, the better the soil desalination effect.

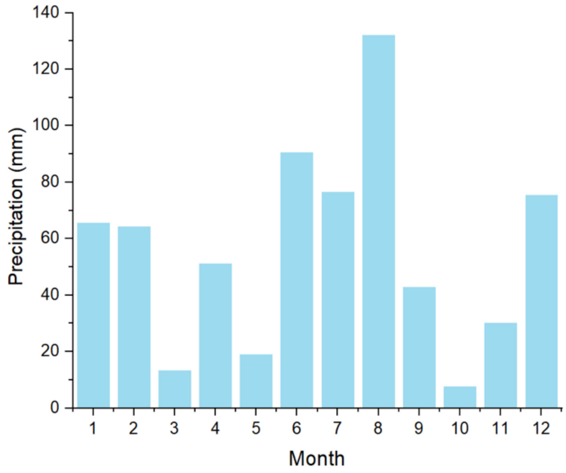

Figure 5. Monthly precipitation variation in the study area (2022).

3.2. Effects of Distance between Observation Well and Drainage Outlet on Soil Salinity

The dynamic transformation process of the longitudinal distribution of salt in every observation layer for each measuring point within the drainage area with a spacing of 11 m from throughout the experiment is depicted in Figure 5.

Based on Figure 6, it is evident that the soil salinity levels near the drainage outlet were lower than those located farther away in every soil layer. Moreover, the decreasing trend of soil salinity levels was uniform throughout the three treatments. Furthermore, the salinity level increased as the measurement point moved farther away from the drainage outlet.

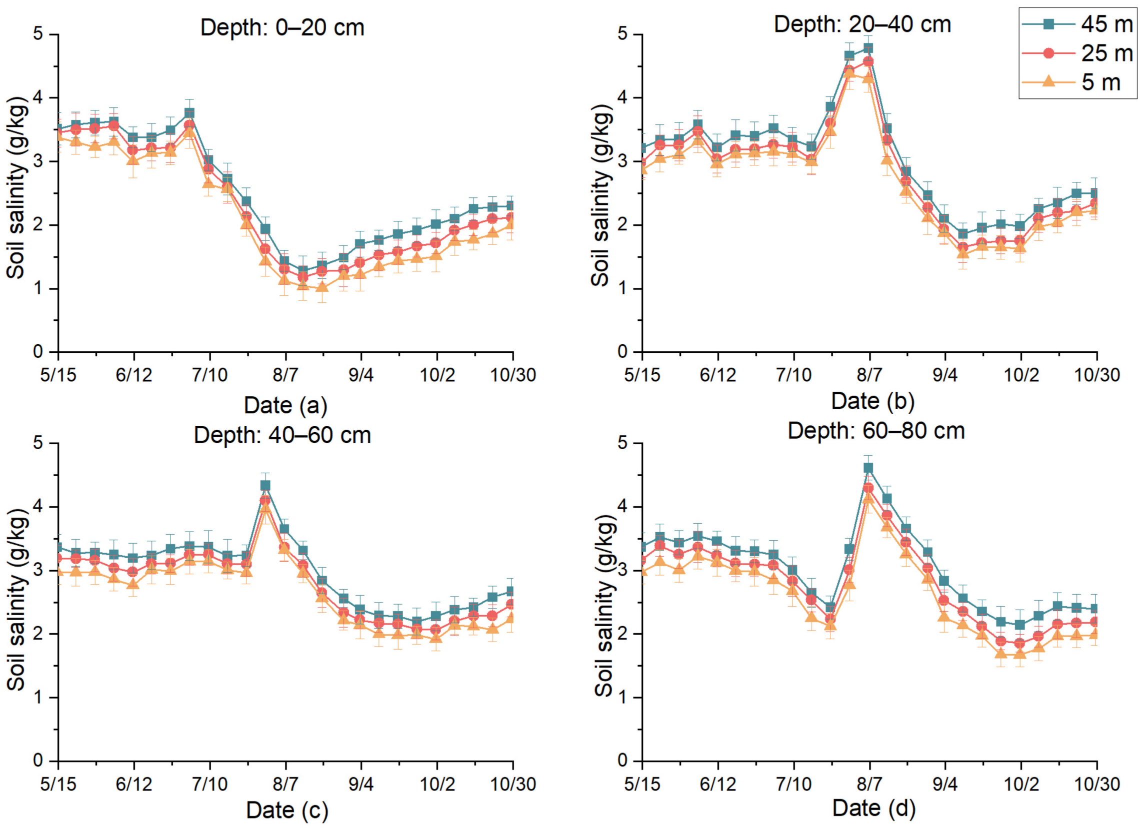

Figure 6. The variation of soil salinity content under different experimental treatments with a subsurface drain spacing of 11 m.

As with the fluctuations in soil salinity levels among varying subsurface drainage pipe spacing treatments, there was a comparable pattern in May–August soil salinity changes, whereby the soil salinity levels reduced significantly within the 0–20 cm soil layer (Figure 6a) while increasing to a greater extent within the deeper 20–80 cm layer (Figure 6b–d).

3.3. Effects of Buried Depth of Subsurface Pipe outlet on Soil Salinity

The desalination rates of the 0–80 cm soil layer before and after leaching for different buried depths of subsurface pipe outlets are shown in Table 5.

Table 5. Desalination rate of 0–80 cm soil layer under different buried depths of subsurface pipe outlets (%).

Depth/cm	40 cm Control Outlet Depth 6 m Subsurface Pipe Spacing	60 cm Control Outlet Depth 11 m Subsurface Pipe Spacing	80 cm Control Outlet Depth 15 m Subsurface Pipe Spacing
0~20	90.5	84.9	80.4
20~40	79.9	65.1	62.4
40~60	30.0	23.2	16.0
60~80	−67.9	−59.8	−43.2
Average	33.1	28.35	28.9

Table 5 demonstrates the significant effectiveness of irrigation leaching in reducing soil surface salinity. During the leaching process, the topsoil undergoes desalination treatment, with desalination rates exceeding 80% across all treatments, effectively addressing surface salt accumulation. Significant desalination occurs in the 0–60 cm soil layer after leaching, indicating positive desalination rates. However, the 60–80 cm soil layer experiences negative desalination, resulting in an average desalination rate of approximately 30%. Decreasing the spacing between underground pipelines leads to increased desalination rates in the 0–60 cm soil layer, while the salt content in the 60–80 cm soil layer increases as upper-layer salts accumulate in the lower soil layers due to water absorption. Similarly, decreasing burial depth exhibits a similar trend. The experimental results indicate that when the burial depth of underground pipelines is 40 cm and the spacing between pipelines is 6 m, the average desalination rate of the 0–80 cm soil layer reaches its highest point, with a desalination rate of the surface 0–20 cm soil layer reaching 90.5%.

3.4. Effects of Subsurface Drainage Pipe Spacing on the Yield of a Salt-Tolerant Crop

The experimental area consists of saline soil primarily dominated by sodium chloride (NaCl), with a total salt content of less than 4 g/kg in the surface soil (Figure 7). In contrast, the control area without subsurface drainage exhibits higher salt levels. However, the other three areas, which have different spacing treatments of subsurface drainage pipes, show relatively lower salt content. These specific conditions have been implemented to cater to the growth requirements of *Sesbania*.

According to Figure 8, the yield of *Sesbania* is ranked in descending order as follows: Zone C > Zone B > Zone A > Control group. The yield in Zone A, Zone B, and Zone C (the subsurface drain spacing of the three experimental areas was 15 m, 11 m, and 6 m, respectively) increased by 10.0%, 15.3%, and 18.1%, respectively, compared to the control group. Additionally, the yields in Zone B and Zone C increased by 4.8% and 7.4%, respectively, compared to Zone A. The yield in the experimental area with a subsurface drain spacing of 6 m increased by 4.8% compared to the experimental area with a subsurface drain spacing of 11 m. It can be observed that the subsurface drainage areas have significantly higher yields, with increases of more than 10% compared to the control area. However, the yield differences among the 15 m, 11 m, and 6 m spacing areas are relatively insignificant. The experimental results show that subsurface drainage has a significant impact on the yield of *Sesbania* compared to natural drainage. Compared to the control group, all three experimental areas with different subsurface drain spacings showed an increase in crop yield of over 10%. However, the yield differences among the different subsurface drain spacing experimental areas were not significant. The results of the ANOVA indicated that the effect of drainage pipe spacing on the yield of a salt-tolerant crop was significant ($p < 0.05$).

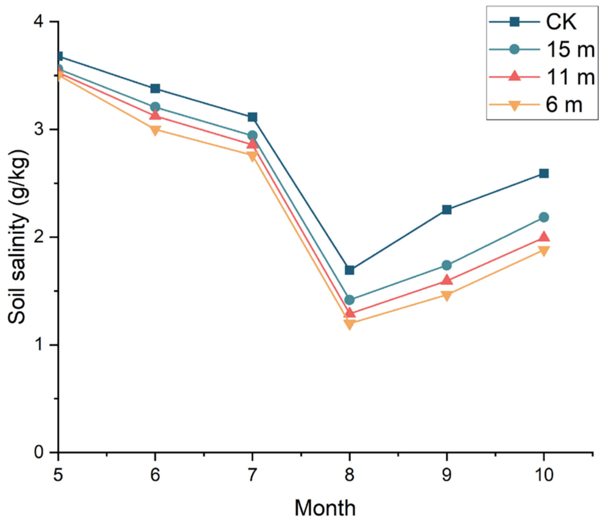

Figure 7. The salt content chart of the surface soil in the experimental area.

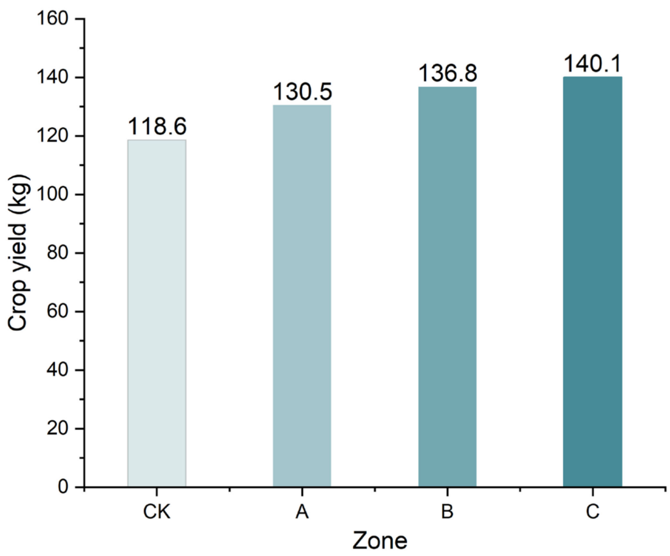

Figure 8. Crop yield chart in each experimental area.

4. Discussion

At the end of the experimental period, the salt content within the 0–80 cm soil layer decreased; however, the degree of salinity reduction varied across different layers. The highest reduction occurred in the 20–40 cm layer, followed by the 40–60 cm, 60–80 cm, and 0–20 cm layers, respectively, indicating that the subsurface drainage system reduced salt content in the topsoil (20 cm depth) by about 80%. In this experiment, no additional water was supplied through artificial irrigation and the water needs of the plants were primarily fulfilled by natural rainfall. Winter rainfall had no significant effect on the leaching of salt content. In September and October, with a decrease in rainfall, the salt in the deeper soil layers and groundwater gradually migrated upwards and accumulated in the surface soil, leading to an increase in soil salinity in the 0–20 cm layer and resulting in the phenomenon of surface accumulation. This was in line with previous research findings, resulting in better salt reduction effects [40–42]. This study has provided further clarification on the optimal spacing range for subsurface drainage pipes, based on earlier studies. These findings have guided the establishment of engineering parameters.

Previous studies have investigated the impact of various drainage depths, drainage spacing, construction areas, and outlet types on soil salinity [19,30,31,43]. However, there is a dearth of research exploring the effect of the distance between the observation well and drainage outlet on soil salinity. The findings of this study are helpful in clarifying the optimal length of subsurface drainage pipes and the layout of field plots. Thus, this study examined the effect of this variable on soil salinity, and the experiment revealed that the changes in salt content of the distance between observation wells and drainage outlets are in line with the changes observed in subsurface drainage pipes at different intervals. From May to August, there was a significant decrease in soil salinity within the 0–20 cm layer and a corresponding increase in soil salinity in the 20–80 cm layer, which can be attributed to the salt being washed down into the deeper soil layers or groundwater. In September and October, with a further reduction in rainfall and the influence of crop transpiration, the salt in the deeper layers of soil and groundwater moved up and accumulated in surface soil, leading to an increase in soil salinity within the 0–20 cm layer and a phenomenon of surface accumulation. And the proximity to the drainage outlet results in a shorter drainage pathway, which in turn leads to a faster drainage velocity.

In India and other developing nations, it is recommended that the buried depth of the subsurface drainage tube should be greater than 1.2 m, ideally between 1.2 m and 1.8 m [44]. However, in China, the buried depth of the subsurface drainage tube should be greater than 0.6 m. This study has demonstrated that in the coastal areas of Jiangsu, China, managing drainage through subsurface drainage pipes with varying depths of drainage outlet burial can effectively lower groundwater levels and enhance soil desalination [45]. These findings provide experimental evidence for a water-saving and salt-controlling irrigation and drainage project model for saline-alkali lands. They are beneficial for further guiding the setting of parameters for subsurface drainage pipes. In subsequent research work, the construction cost will be comprehensively considered to further clarify the appropriate range of buried depths for subsurface drainage pipes.

According to the salt transport principle (Figure 9), after leaching, surface soil salt penetrates into deeper soil layers or groundwater and is then discharged through the drainage system. The movement of salt in the soil is primarily influenced by changes in moisture content. The subsurface drainage system, such as a buried pipe system, provides a pathway for water movement in agricultural fields. As the spacing between underground drainage pipes increases, the drainage capacity of the pipes decreases [37,38]. This is because smaller pipe spacing and shallower burial depth result in a higher hydraulic gradient and greater water infiltration intensity, leading to more pronounced flow convergence. Consequently, the migration distance of salt decreases, and the desalination rate increases. Salt continuously accumulates in the subsurface drainage pipes and is subsequently discharged, resulting in better desalination effects. Therefore, based on our research, we recommend adopting optimal parameters for subsurface drainage design, including a pipe spacing of 6 m and a burial depth of 40 cm for the drainage outlets.

Subsurface drainage has proven to be effective in reducing the salt content of soil surfaces and enhancing crop yield [46]. Rainfall can quickly leach the salt content from the topsoil (0–20 cm). The smaller the spacing between subsurface drainage pipes, the faster the drainage speed, resulting in a quicker removal of soil salt content and a reduction in residual salt content in the topsoil. While rapid drainage is beneficial, it also means that nutrients can be lost along with the water. Therefore, a controlled subsurface drainage system is necessary to manage nutrient loss effectively. The implementation of a subsurface drainage system, utilizing underground pipes and controlled field drainage, helps in retaining nitrogen within the soil during rainfall. This, in turn, reduces losses caused by surface runoff and leaching, while ensuring an adequate supply of nutrients for plant growth. As a result, crop yields are increased.

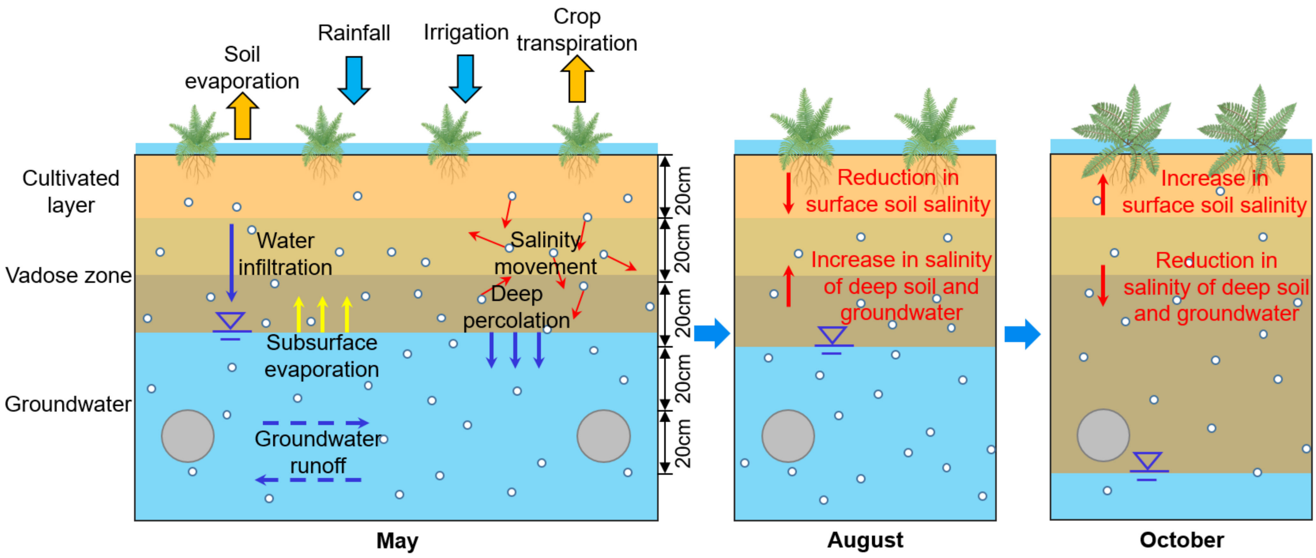

Figure 9. Salt movement in the experimental area soil (from May to October 2022).

5. Conclusions

This study analyzed the impact of factors such as the spacing of subsurface drainage pipes, the distance between observation wells and drainage outlets, and the buried depths of subsurface pipe outlets on soil salinity movement and proposes an optimal layout for subsurface drainage pipes. The research provides theoretical references and technical support for efficient and rapid desalination technology in saline-alkaline land in coastal areas. The key findings of this study are:

1. With the longitudinal distance between observation wells and drainage outlets consistently maintained, soil salt content changes over time in a consistent trend with the draining of subsurface drainage pipes (with subsurface drainage pipe spacings of 6 m, 11 m, and 15 m). Subsurface drainage pipes can also effectively decrease soil salt accumulation and reduce the degree of salinization. Furthermore, subsurface drainage can significantly increase the yield of a salt-tolerant crop (*Sesbania*), but there is no significant difference in yield between different subsurface drainage spacings.
2. When the subsurface drainage pipe spacing remains unchanged, placing subsurface drainage pipes closer to the drainage outlet leads to a better desalinization effect on the soil.
3. When the subsurface drainage pipe spacing is constant, increasing the drainage outlet depth of subsurface drainage pipes can lower the groundwater level and effectively decrease soil salt accumulation.

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References

1. The State of Food Security and Nutrition in the World 2021. Available online: https://www.who.int/publications/m/item/the-state-of-food-security-and-nutrition-in-the-world-2021 (accessed on 1 October 2022).
2. The Total Area of Saline-Alkali Land in China Is about 99 Million Hectares. The Yellow River Delta Experimental Station Has Been Built. Available online: https://baijiahao.baidu.com/s?id=1744769950363357466&wfr=spider&for=pc (accessed on 23 September 2022).
3. Heng, T.; Liao, R.; Wang, Z.; Wu, W.; Li, W.; Zhang, J. Effects of combined drip irrigation and sub-surface pipe drainage on water and salt transport of saline-alkali soil in Xinjiang, China. *J. Arid Land* **2018**, *10*, 932–945. [CrossRef]
4. Cheng, Y.; Xie, X.; Wang, X. Effects of the Salt-Tolerant Gramineous Forage Echinochloa frumentacea on Biological Improvement and Crop Productivity in Saline–Alkali Land on the Hetao Ningxia Plain in China. *Sustainability* **2023**, *15*, 5319. [CrossRef]
5. Wang, S.J.; Chen, Q.; Li, Y.; Zhuo, Y.Q.; Xu, L.Z. Research on saline-alkali soil amelioration with FGD gypsum. *Resour. Conserv. Recycl.* **2017**, *121*, 82–92. [CrossRef]
6. Li, Y.; Li, G. Mechanisms of straw biochar's improvement of phosphorus bioavailability in soda saline-alkali soil. *Environ. Sci. Pollut. Res.* **2022**, *29*, 47867–47872. [CrossRef] [PubMed]
7. Wang, J.; Dun, Y.; Guo, Y. Effects of land consolidation on improvement of salinity soil in Western Songnen Plain. *Trans. Chin. Soc. Agric. Eng.* **2014**, *30*, 266–275.
8. Zhao, L.; Heng, T.; Yang, L. Study on the farmland improvement effect of drainage measures under film mulch with drip irrigation in saline–alkali land in arid areas. *Sustainability* **2021**, *13*, 4159. [CrossRef]
9. Naftchali, D.A.; Abdullah, R.H.; Karandish, F.; Bidgoli, M.A.; Nasr, M.G. Alternate wetting and drying for different subsurface drainage systems to improve paddy yield and water productivity in Iran. *Agric. Water Manag.* **2017**, *193*, 221–231. [CrossRef]
10. Sheoran, P.; Basak, N.; Kumar, A.; Yadav, R.K.; Singh, R.; Sharma, R.; Kumar, S.; Singh, R.K.; Sharma, P.C. Ameliorants and salt tolerant varieties improve rice-wheat production in soils undergoing sodification with alkali water irrigation in Indo–Gangetic Plains of India. *Agric. Water Manag.* **2021**, *243*, 106492. [CrossRef]
11. Talukolaee, M.J.; Naftchali, A.D.; Parvariji, L.Z. Investigating long−term effects of subsurface drainage on soil structure in paddy fields. *Soil Tillage Res.* **2018**, *177*, 155–160. [CrossRef]
12. Luthin, J.N.; Luthin, J.N. *Drainage Engineering*; Wiley: New York, NY, USA, 1966.
13. He, X.L.; Liu, H.G.; Ye, J.W. Comparative investigation on soil salinity leaching under subsurface drainage and ditch drainage in Xinjiang arid region. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 109–118.
14. Smedema, L.K.; Vlotman, W.F.; Rycroft, D.W. *Modern Land Drainage: Planning, Design and Management of Agricultural Drainage Systems*; Taylor and Francis Group: London, UK, 2004.
15. Azhar, A.H. Impact of Subsurface Drainage on Soil Salinity in Pakistan. *J. Anim. Plant Sci.* **2010**, *20*, 62–68.
16. Wan, C.Y.; Zhang, Z.Y.; Feng, G.X.; Chen, Y.; Lu, P.R. Transport Feature of Soil Water-salt by Saline Water Irrigation under Subsurface Pipe Drainage. *J. Irrig. Drain* **2016**, *35*, 37–41. (In Chinese)
17. Kladivko, E.J.; Frankenberger, J.R.; Jaynes, D.B.; Meek, D.W.; Jenkinson, B.J.; Fausey, N.R. Nitrate Leaching to Subsurface Drains as Affected by Drain Spacing and Changes in Crop Production System. *J. Environ. Qual.* **2004**, *33*, 1803. [CrossRef] [PubMed]
18. Zhang, Y.Z.; Zhang, Z.Y.; Zhang, Z.Y.; Wang, B. Design Parameters of Underground Pipe Engineering in Saline Coastal. *J. Irrig. Drain.* **2011**, *30*, 96–99. (In Chinese)
19. Qian, Y.; Zhu, Y.; Ye, M. Experiment and numerical simulation for designing layout parameters of subsurface drainage pipes in arid agricultural areas. *Agric. Water Manag.* **2021**, *243*, 106455. [CrossRef]
20. Ibrakhimov, M.; Khamzina, A.; Forkutsa, I.; Paluasheva, G.; Lamers, J.P.A.; Tischbein, B.; Vlek, P.L.G.; Martius, C. Groundwater table and salinity: Spatial and temporal distribution and influence on soil salinization in Khorezm region (Uzbekistan, Aral Sea Basin). *Irrig. Drain. Syst.* **2007**, *21*, 219–236. [CrossRef]
21. Haj, A.Z.; Bouri, S. Subsurface Drainage System Performance, Soil Salinization Risk, and Shallow Groundwater Dynamic under Irrigation Practice in an Arid Land. *Arab. J. Sci. Eng.* **2019**, *44*, 467–477.
22. Hanson, B.R.; Ayars, J.E. Strategies for reducing subsurface drainage in irrigated agriculture through improved irrigation. *Irrig. Drain. Syst.* **2002**, *16*, 261–277. [CrossRef]
23. Christen, E.W.; Ayars, J.E. *Subsurface Drainage System Design and Management in Irrigated Agriculture: Best Management Practices for Reducing Drainage Volume and Salt Load*; CSIRO Land and Water: Clayton South, Australia, 2001.
24. Li, S.; Bhattarai, R.; Cooke, R.A. Assessment of surface inlets performance on sediment transport to subsurface drainage system. *Appl. Eng. Agric.* **2017**, *33*, 217. [CrossRef]
25. Xin, P.; Dan, H.C.; Zhou, T. An analytical solution for predicting the transient seepage from a subsurface drainage system. *Adv. Water Resour.* **2016**, *91*, 1–10. [CrossRef]

26. Wang, L.J.; Song, Q.C.; Wu, W.; Cao, S.Y. Variation law of groundwater depth and mineralization of coastal tidal flats in Jiangsu Province. *Adv. Sci. Technol. Water Resour.* **2021**, *41*, 52–57. (In Chinese)
27. Luo, W.; Zhang, Y.; Yang, X.; Li, Y.J.; Cai, S.C. Simulating the effects of subsurface drainage on winter wheat yield in coastal reclamation areas of Jiangsu, China. *Trans. Chin. Soc. Agric. Eng.* **2022**, *38*, 83–91. (In Chinese)
28. Ministry of Agriculture and Rural Affairs of the People's Republic of China. Classification and Grade of Saline-Alkali Soil for Agricultural Use (GB/T 20205107-T-326). 2020. Available online: https://std.samr.gov.cn/gb/search/gbDetailed?id=A944D43C8FABBF44E05397BE0A0A276C (accessed on 24 December 2020). (In Chinese)
29. Bao, S. *Soil Agricultural Chemistry Analysis*, 3rd ed.; China Agriculture Press: Beijing, China, 2000.
30. Sharma, D.P.; Singh, K.; Rao, K. Subsurface drainage for rehabilitation of waterlogged saline lands: Example of a soil in semiarid climate. *Arid Soil Res. Rehabil.* **2000**, *14*, 373–386. [CrossRef]
31. Nozari, H.; Azadi, S.; Zali, A. Experimental study of the temporal variation of drain water salinity at different drain depths and spacing in the presence of saline groundwater. *Sustain. Water Resour. Manag.* **2018**, *4*, 887–895. [CrossRef]
32. Guo, X.Q. Preliminary Study on High-Yielding Cultivation of *Sesbania cannabina* in Saline Soil. Master's Thesis, Yangzhou University, Yangzhou, China, June 2019. (In Chinese)
33. Jing, Y.P.; Lin, C.Y.; Zhao, P.Y.; Li, X.P.; Zhao, Q.; Liu, Y.J.; Liu, M.; Tuo, D.B.; Wang, L.J.; Yang, X. Salinized soil improvement by planting 5 plant species in Hetao irrigation area. *Soils Crops* **2020**, *9*, 114–125. (In Chinese)
34. Pan, J.; Wang, L.Y.; Xiao, H.; Chen, W.J.; Yang, Y. Dynamic Changes of Soil Nutrients of Salt-tolerant Herbaceous Plants in Coastal Saline Soil. *Chin. Agric. Sci. Bull.* **2015**, *31*, 168–172. (In Chinese)
35. Huang, L.P.; Wang, L.Y.; Yang, Y.; Xiao, H.; Cheng, W.J.; Pan, J. The Characteristics of Soil Movement in Coastal Saline Soil of Four Salt-tolerant Plants. *Tianjin Agric. Sci.* **2014**, *20*, 73–76. (In Chinese)
36. Sheng, F.; Xiuling, C. Influence of atmospheric precipitation on soil leaching and desalinization in semi-humid region. In Proceedings of the 13th International Soil Conservation Organization Conference, Conserving Soil and Water for Society: Sharing Solutions, Brisbane, Australia, 4–8 July 2004.
37. Bahceci, I.; Nacar, A.S. Subsurface drainage and salt leaching in irrigated land in south-east Turkey. *Irrig. Drain. J. Int. Comm. Irrig. Drain.* **2009**, *58*, 346–356.
38. Chahar, B.R.; Vadodaria, G.P. Drainage of ponded surface by an array of ditches. *J. Irrig. Drain. Div. Am. Soc. Civ. Eng.* **2008**, *134*, 815–823. [CrossRef]
39. Chahar, B.R.; Vadodaria, G.P. Steady subsurface drainage of homogeneous soils by ditches. In *Proceedings of the Institution of Civil Engineers-Water Management*; Thomas Telford Ltd.: London, UK, 2008; Volume 161, pp. 303–311.
40. Ayars, J.E.; Shouse, P.; Lesch, S.M. In situ use of groundwater by alfalfa. *Agric. Water Manag.* **2009**, *96*, 1579–1586. [CrossRef]
41. Ayars, J.E.; Christen, E.W.; Soppe, R.W.; Meyer, W.S. The resource potential of in-situ shallow ground water use in irrigated agriculture: A review. *Irrig. Sci.* **2006**, *24*, 147–160. [CrossRef]
42. Ayars, J.E.; Christen, E.W.; Hornbuckle, J.W. Controlled drainage for improved water management in arid regions irrigated agriculture. *Agric. Water Manag.* **2006**, *86*, 128–139. [CrossRef]
43. Madramootoo, C.A. Planning and design of drainage systems. *Agric. Drain.* **1999**, *38*, 871–892.
44. Tiwari, P.; Goel, A. An overview of impact of subsurface drainage project studies on salinity management in developing countries. *Appl. Water Sci.* **2017**, *7*, 569–580. [CrossRef]
45. Yang, Y.; Li, D.; Huang, W. Effects of Subsurface Drainage on Soil Salinity and Groundwater Table in Drip Irrigated Cotton Fields in Oasis Regions of Tarim Basin. *Agriculture* **2022**, *12*, 2167. [CrossRef]
46. Wang, Z.; Shao, G.; Lu, J. Effects of controlled drainage on crop yield, drainage water quantity and quality: A meta-analysis. *Agric. Water Manag.* **2020**, *239*, 106253. [CrossRef]