Research Progress and Prospects of Saline Water Freezing Irrigation for Saline-Alkali Land Amelioration: A Postprint

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Abstract

Winter saline water ice irrigation technology is an effective means for utilizing high-salinity saline water and improving saline-alkali land in coastal areas. This technology is based on the fundamental principle of saline-fresh water separation during the freezing and melting process of saline water. Grounded in regional climate characteristics, soil water-salt transport patterns, and crop growth and development laws, it involves extracting local high-salinity groundwater to irrigate saline-alkali land in winter, which rapidly freezes into saline ice under low winter temperatures. During the melting of the saline ice layer in spring, saline and fresh water separate and infiltrate. The high-salinity water that melts first infiltrates initially, while the subsequent infiltration of low-salinity brackish water and fresh water that melts later effectively leaches soil salts. This process achieves soil desalination during the spring period when salts typically return to the soil surface. Combined with spring surface cover salt suppression measures and summer rainfall leaching, low-salt conditions are maintained in the soil, ensuring normal growth of crops and plants throughout their entire growth period. This technology alters soil water-salt transport characteristics in coastal saline-alkali areas, transforming the spring soil salt accumulation period into a desalination period. Following saline water ice irrigation, spring topsoil salinity rapidly decreases from the initial 12g kg 1 to below 4 g kg 1, with a desalination rate exceeding 66%. This has enabled the cultivation of crops such as cotton, oil sunflower, and sugar beet in coastal heavy saline-alkali land, and improved the survival rates of cutting transplanting for halophytes and salt-tolerant plants including tamarisk, goji berry, and ash. In the year of saline water ice irrigation, seed cotton yields of 3 t hm 2, oil sunflower yields of 1.5 t hm 2, and sugar beet yields of 60 t hm 2 were obtained, along with over 90% survival rates for halophyte and salt-tolerant plant cuttings, thereby promoting the development of saline-alkali land, agricultural advancement, and ecological environment construction in coastal saline-alkali areas. In recent years, through systematic research, we have elucidated the separation patterns of saline-fresh water during the freeze-thaw process in saline water ice irrigation, clarified the leaching effects of saline water ice irrigation on soil salinity, constructed a technical system for improving saline-alkali land through winter saline water ice irrigation, and established indicator systems for irrigation timing, water volume, and water quality for winter saline water ice irrigation. Building upon the aforementioned research, this paper summarizes research progress on saline water utilization in saline-alkali land, provides an overview of the fundamental principles, influencing factors, and soil salt leaching effects of saline water ice irrigation, systematically analyzes the role of winter saline water ice irrigation in agricultural production, vegetation restoration, and saline water utilization in saline-alkali regions, and discusses its future development trends.

Full Text

Preamble

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Advances and Expectations of Research on Saline Soil Reclamation by Freezing Saline Water Irrigation

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Abstract

Winter freezing saline water irrigation technology represents an effective approach for utilizing highly mineralized saline water and reclaiming saline soils in coastal regions. This technique is based on the fundamental principle of saline-fresh water separation during the freezing and thawing of saline water. By integrating regional climate characteristics, soil water and salt movement patterns, and crop growth dynamics, highly mineralized groundwater is pumped and applied to saline lands during winter, where it rapidly freezes into saline ice under low temperatures. During spring thawing, the saline-fresh water separation process occurs through infiltration: the initially melted high-salinity water infiltrates first, followed by subsequently melted low-salinity brackish water and freshwater, which effectively leaches soil salts. This process achieves soil desalination during the spring salt-return period. Combined with spring surface mulching for salt suppression and summer rainfall leaching, low-salt conditions are maintained throughout the crop growth period, ensuring normal plant development. This technology alters the characteristics of soil water and salt movement in coastal saline regions, transforming the spring soil salt accumulation period into a desalination period. Following freezing saline water irrigation, topsoil salinity rapidly decreases from an initial 12 g · kg ^{1} to below 4 g · kg ^{1}, achieving a desalination rate exceeding 66%. This has enabled cultivation of crops such as cotton, oil sunflower, and sugar beet in heavy coastal saline soils, while improving the transplant survival rates of halophytes and salt-tolerant plants including tamarisk, wolfberry, and Chinese ash. In the first year after implementation, yields reached 3 t · hm ^{2} for seed cotton, 1.5 t · hm ^{2} for oil sunflower, and 60 t · hm ^{2} for sugar beet, with cutting and transplanting survival rates exceeding 90% for halophytes and salt-tolerant plants. The technology has promoted saline land development, agricultural production, and ecological construction in coastal saline regions. Recent systematic research has elucidated the separation patterns of saline-fresh water during freezing and thawing, clarified the soil salt leaching effects of freezing saline water irrigation, and established a technical system with defined indices for irrigation timing, water volume, and water quality. This paper synthesizes research progress on saline water utilization in saline soils, summarizes the basic principles, influencing factors, and salt leaching effects of freezing saline water irrigation, systematically analyzes its roles in agricultural production, vegetation restoration, and saline water utilization in saline regions, and discusses future development trends.

Keywords: Saline soil reclamation; Saline water utilization; Freezing saline water irrigation; Vegetation restoration; Soil salt leaching

1. Soil Water-Salt Dynamics During Soil Freezing Processes

Soil salt movement exhibits distinct seasonal patterns, strong surface accumulation, complex types, and repeated cycles of salt accumulation and leaching. Water and salt transport are primarily influenced by rainfall and evaporation. Taking the low-lying coastal plain region around the Bohai Sea as an example [Figure 1: see original paper], soil salinity dynamics show salt accumulation in spring, autumn, and winter, with desalination occurring in summer. Soil freezing and thawing from winter to spring are accompanied by water and salt movement, where soil freezing represents a potential salt accumulation process, while spring thawing and evaporation cause "explosive" salt accumulation. Research by Zhang Dianfa et al. indicates that during soil freezing, the soil profile can be divided into three layers: the frozen layer, the quasi-frozen layer, and the non-frozen layer, from top to bottom. Soil freezing involves the phase transition of water from liquid to solid, reducing water potential in the frozen layer and driving water and salt migration from deeper soil layers toward the frozen layer, gradually increasing water and salt content. The quasi-frozen layer below the frozen layer continuously moves downward as the frozen layer thickens, with water and salt continuously accumulating in the frozen layer. Spring thawing and evaporation cause intense salt return to the surface. Soil thawing occurs at both upper and lower fronts of the frozen layer: meltwater and salts from the lower front migrate directly to deeper layers, while the upper front thaws faster. Melted water and salts are blocked by the remaining frozen layer and accumulate above it, rapidly concentrating in the surface soil through evaporation until the entire frozen layer thaws—this is the direct cause of "explosive" salt accumulation in spring. Subsequently, soil salt leaching and re-accumulation occur with summer and autumn rainfall and evaporation.

Different saline soil types possess varying physical and chemical properties, complicating reclamation efforts. Site-specific integrated approaches should be adopted based on specific soil characteristics. Currently, water conservancy measures centered on "freshwater salt leaching" represent the most effective reclamation method. However, freshwater scarcity in saline regions limits this approach, making the rational utilization of abundant groundwater saline water an urgent issue for agricultural production.

2. Current Status of Saline Water Utilization

Against the backdrop of freshwater scarcity, abundant groundwater saline water in saline regions has become a potential agricultural water resource. Research shows that saline water irrigation can alleviate drought caused by freshwater shortages and even increase crop yields without degrading soil properties. However, improper use can lead to soil degradation and yield reduction, making rational saline water utilization a critical research direction in agricultural irrigation. Extensive research has been conducted on soil water-salt movement under saline water irrigation, revealing that irrigation volume, water quality, and soil conditions significantly affect water-salt transport. Studies demonstrate that saline water irrigation volume critically influences salt leaching, with effective leaching achieved through adequate volumes and deeper desalination with increased infiltration. Pang Huancheng et al. noted that insufficient single irrigation volumes can leave salts in the surface soil. Water mineralization is another key factor; excessively high salinity causes salt accumulation. Xiao Zhenhua et al. found that when irrigation water mineralization is below $3\ \mathrm{g}\cdot\mathrm{L}^{\ 1}$, soil profile salt remains balanced, but exceeds this threshold leads to varying degrees of salt accumulation. Besides mineralization, the Sodium Adsorption Ratio (SAR) is a crucial water quality indicator, calculated as $\mathrm{SAR} = \mathrm{Na}\ /\sqrt{}((\mathrm{Ca}^{2}\ \ +\mathrm{Mg}^{2}\ )/2)$ with ion units in $\mathrm{mmol}\cdot\mathrm{L}^{\ 1}$. SAR significantly affects salt leaching: while salts can stabilize soil structure and improve hydraulic conductivity, excessive Na disperses soil particles and reduces permeability. Soil type also influences infiltration and leaching, with saline water affecting alkaline soils more than saline soils. Additionally, water-salt dynamics are affected by irrigation methods and scheduling. Drip irrigation better regulates root zone salt conditions and yields higher crop production than flood, furrow, or sprinkler irrigation. Saline water irrigation can also be combined with freshwater through mixing or rotational irrigation for improved leaching effects.

3. Principles and Technical System of Freezing Saline Water Irrigation for Saline Soil Reclamation

3.1 Technical Principles of Saline Water Desalination and Freezing Irrigation

Current saline water irrigation research primarily focuses on low-salinity water (<5 g · L ^{1}), as high-salinity water is considered unsuitable for direct irrigation due to risks of soil salinization and degradation. However, groundwater in saline regions is generally highly mineralized; for example, shallow groundwater in the Bohai Sea coastal saline region exceeds 7 g · L ^{1}. Saline water desalination technologies have been proposed to address this challenge, including freezing-thawing, distillation, electrodialysis, and reverse osmosis. Distillation, electrodialysis, and reverse osmosis involve complex infrastructure and high costs, mainly for drinking water supply. Freeze-thaw desalination utilizes freezing and melting processes to separate saline and fresh water [Figure 2: see original paper], with melting showing significantly better desalination than freezing. Frozen saline water is a mixture of ice crystals, brine pockets, air bubbles, and solids, where salts exist primarily in brine pockets that interconnect during melting, creating channels for salt leaching. Recent studies on sea ice desalination for agricultural irrigation have shown promising results, but collection, transportation, and storage limitations restrict widespread application.

Considering these constraints and based on regional climate and soil water-salt dynamics, we proposed winter freezing saline water irrigation. This approach leverages low winter temperatures in northern saline regions to directly pump local groundwater for irrigation, which rapidly freezes. During spring thawing, the subsequently melted brackish and freshwater effectively leaches soil salts. Combined with subsequent rainfall and salt suppression measures, this creates low-salt conditions for crop emergence and plant growth throughout the growing season.

3.2 Improvement Effects and Influencing Factors

3.2.1 Improvement Effects Since implementation, freezing saline water irrigation has demonstrated significant saline soil reclamation effects, attributable to the remarkable desalination during freeze-thaw processes. Laboratory studies show that melting 15 g · L ^{1} saline ice at room temperature produces over 50% brackish water and freshwater with mineralization below 3 g · L ^{1}, with SAR decreasing as melting progresses. Field application using 13.5 g · L ^{1} saline water for winter freezing irrigation produces over 75% low-salinity meltwater that effectively leaches soil salts. The ice layer moderates soil temperature, increases soil temperature by approximately 1°C with 180 mm irrigation, reduces frozen layer depth by 8.5 cm, and decreases salt accumulation in the frozen layer by 19.8%. After complete melting and infiltration, root zone (0–40 cm) salinity rapidly decreases from over 10 g · L ^{1} to below 3 g · L ^{1}, achieving desalination rates exceeding 70%. With spring surface mulching, soil salinity remains below

4 g • kg ^{1}, allowing safe passage through the spring salt-return peak. Film and residue mulching prove most effective. Summer rainfall further ensures normal crop growth, yielding ideal production in the first year: cotton emergence rates exceed 80%, halophyte cutting survival exceeds 90%, with yields of 3 t • hm ^{2} seed cotton, 1.5 t • hm ^{2} oil sunflower, and 60 t • hm ^{2} sugar beet. Long-term application progressively reduces soil salinity and SAR while increasing crop yields. Laboratory studies show saline ice meltwater infiltrates coastal saline soil faster and deeper than freshwater ice, with better leaching effects, likely because initially melted high-salinity water improves soil structure for subsequent low-salinity water infiltration. Surface soil (0–20 cm) salinity decreases from 21.2 g • L ^{1} to 2.5 g • L ^{1} after infiltration, achieving over 95% desalination, with Na and Cl migrating faster than other ions.

3.2.2 Influencing Factors The salt leaching effectiveness of freezing saline water irrigation is influenced by multiple factors. Results from different mineralization and water volumes show that higher water volumes produce more low-salinity meltwater, increasing infiltration speed, depth, and leaching effectiveness. Using 10 g • L ^{1} saline ice with volumes of 90 mm, 135 mm, and 180 mm achieved surface soil (0–20 cm) desalination rates of 29.7%, 56.7%, and 96.2%, respectively. At constant volume, higher mineralization increases infiltration speed and depth while improving leaching effectiveness. Using 180 mm of 5, 10, and 15 g • L ^{1} saline ice achieved surface soil desalination rates of 95.7%, 96.2%, and 96.3%, respectively. SAR also significantly affects infiltration and leaching: high SAR reduces soil permeability, slowing infiltration and decreasing desalination effectiveness. However, saline ice consistently outperforms freshwater ice, with SAR 5, 10, and 30 treatments achieving 92.5%, 89%, and 87% desalination rates, respectively, all significantly higher than the 80% freshwater treatment. Soil conditions including soil type, water-salt status, and bulk density also affect leaching. Saline ice meltwater infiltrates soda alkaline soils faster than coastal saline soils (23.44 times vs. 2.54 times faster than freshwater), though leaching effectiveness is lower in soda alkaline soils due to ion composition. Soil moisture content significantly affects leaching: higher moisture content slows infiltration and salt migration. Additional factors requiring further research include groundwater depth and quality, soil physicochemical properties, and soil freezing-thawing effects on meltwater infiltration and salt leaching.

3.3 Technical System for Winter Freezing Saline Water Irrigation

Based on comprehensive research, we have established a technical system for saline soil reclamation through freezing saline water irrigation, defining indices for irrigation timing, water quality, volume, and supporting measures.

3.3.1 Determination of Irrigation Timing Table 1 shows soil salinity changes under different irrigation timings. Irrigation is recommended when daily average temperatures drop below -5°C in mid-to-late January, ensuring stable ice formation and effective salt leaching. Late irrigation results in poor freezing and unfavorable desalination due to freeze-thaw salt accumulation.

3.3.2 Determination of Irrigation Water Volume The irrigation volume can be determined based on water quality using binary regression equations for saline ice melting. The leaching quota equation for freezing saline water irrigation is:

$$V = \frac{M}{s_Y}$$

where V is the freezing saline water irrigation quota (m^3 · hm ^{2}), M is the freshwater leaching quota (m^3 · hm ^{2}), and s_Y is the percentage of meltwater with different mineralization levels (%).

The freshwater leaching quota is calculated based on simplified salt movement theory, assuming vertical salt movement and complete mixing:

$$M = \frac{H \cdot \gamma \cdot (\theta_f - \theta_0) \cdot (S_0 - S_a)}{1 - S_a} + e - P$$

where M is the leaching quota (m^3 · hm ^{2}), H is the planned desalination depth (m), θ_f is field capacity (% of dry soil weight), θ_0 is initial soil moisture content (% of dry soil weight), S_0 and S_a are pre-leaching and target soil salinity (excluding salts from irrigation water), γ is soil bulk density, e is evaporation during leaching, and P is rainfall during leaching.

The binary linear equations for saline-fresh water separation during saline ice melting are:

$$Y_{5\,\text{g}\cdot\text{L}^{-1}} = 74.052 - 0.945T_m - 1.018S_i \quad (R^2 = 0.877^{**})$$

$$Y_{4\,\text{g}\cdot\text{L}^{-1}} = 71.867 - 0.536T_m - 0.942S_i \quad (R^2 = 0.803^{**})$$

$$Y_{3\,\text{g}\cdot\text{L}^{-1}} = 66.823 - 0.962T_m - 0.842S_i \quad (R^2 = 0.788^{**})$$

$$Y_{2\,\text{g}\cdot\text{L}^{-1}} = 66.757 - 1.087T_m - 0.879S_i \quad (R^2 = 0.813^{**})$$

$$Y_{1\,\text{g}\cdot\text{L}^{-1}} = 60.365 - 1.148T_m - 0.731S_i \quad (R^2 = 0.759^{**})$$

where Y is the meltwater percentage (%), T_m is melting temperature (°C), and S_i is initial saline ice salinity (g · L ^{1}).

Calculated volumes match actual applications. For heavy coastal saline soils in the Bohai region using 12 g · L ^{1} saline water to reduce salinity from 12 g · L ^{1} to below 4%, the calculated volume is approximately 196 mm (1,954.5 m^{3} · hm ^{2}), while actual applied volume is 180 mm (1,800 m^{3} · hm ^{2}).

3.3.3 Supporting Technical Measures Spring represents the peak salt-return period. Although freezing saline water irrigation significantly reduces soil salinity, strong evaporation can cause rapid re-salinization. Research shows that plastic film mulching after spring meltwater infiltration provides the best salt suppression, followed by straw mulching, maintaining topsoil salinity below 4 g · kg ^{1} until sowing and transplanting. For salt-tolerant crops (cotton, oil sunflower, sugar beet, sweet sorghum), pre-sowing practices include film removal, fertilization, rotary tillage, and timely sowing with film mulching using slow-release fertilizer at 750 kg · hm ^{2} as basal application. For halophytes (tamarisk, wolfberry), cutting and transplanting methods are used, with seedlings transplanted into low-salinity, film-mulched soils, followed by appropriate topdressing during vigorous growth periods.

3.4 Applicability of Winter Freezing Saline Water Irrigation Technology

This technology is based on the principle of separating micro-saline and fresh water from high-salinity water through natural freeze-thaw processes using winter low temperatures. It is applicable to northern saline regions where winter temperatures stably drop to -5°C, enabling stable ice formation and effective spring thawing desalination.

4. Social and Economic Benefits

Saline soil reclamation and safe saline water utilization are critical issues for agricultural development and ecological construction in arid, semi-arid, and coastal regions. Freezing saline water irrigation leverages local climate and saline water resources, conserves freshwater, and provides technical support for saline land improvement. We have established a "two innovations and one integration" system: innovative salt leaching methods (transforming freshwater irrigation to freezing saline water leaching), innovative critical water table management (ensuring seasonal root zone desalination), and integrated reclamation measures. Multiple planting models based on this technology have been developed for salt-tolerant crops (cotton, oil sunflower, sugar beet, sweet sorghum, Jerusalem artichoke) and halophytes (tamarisk, wolfberry), achieving soil salinity below 0.4% with progressive annual decreases. Crop emergence rates exceed 85% for cotton and 90% for other crops, with halophyte transplant survival above 90%. This has driven industrial development in cotton, energy plants, forage, and ecological construction, enabling efficient utilization of previously unusable coastal saline wastelands. The input-output ratio exceeds 1:3, saving over 1,800 m^{3} ·

hm ^{2} of freshwater and significantly reducing agricultural and afforestation costs while promoting coordinated economic, ecological, and social benefits.

5. Conclusions and Outlook

Extensive research has addressed freezing saline water irrigation processes, including desalination effects, meltwater infiltration, salt leaching mechanisms and influencing factors, soil temperature and freeze-thaw dynamics, and long-term soil salinity changes. Key conclusions include: significant desalination during freeze-thaw processes; rapid soil salinity reduction after irrigation; maintained low-salt conditions through spring mulching; faster and deeper infiltration of saline ice meltwater compared to freshwater ice; and influences of water quality, volume, soil type, and moisture on leaching effectiveness. Based on these findings, we have established a technical system defining irrigation timing, volume, water quality, and supporting measures, providing technical support for agricultural production and ecological construction in saline regions.

However, freezing saline water irrigation is a complex, continuous process involving ice melting, infiltration, and water-salt movement, influenced by numerous factors including soil freeze-thaw, groundwater depth and quality, and soil physicochemical properties. Further research is needed in three areas: (1) simulation models of soil water-salt movement under freezing irrigation to reveal patterns of continuous infiltration and long-term salt balance; (2) infiltration patterns of meltwater in frozen-thawing soils, as the melting process involves sequential release of different salinity waters while soils remain in freeze-thaw states; and (3) impacts of shallow saline groundwater on reclamation effectiveness.

References

[1] Wang Z C, Liang Z W. Advances of salt tolerance in plants[J]. Ecology and Environment, 2003, 12(1): 106-109
[2] Liu Y C, He W S, He J Z. Progress of improvement and utilization of saline-alkali land[J]. Journal of Agricultural Sciences, 2007, 28(2): 68-71
[3] Yang J S. Development and prospect of the research on salt affected soils in China[J]. Aca Pedologica Sinica, 2008, 45(5): 837-845
[4] Zhang J F, Zhang X D, Zhou J X, et al. World resources of saline soil and main amelioration measures[J]. Research of Soil and Water Conservation, 2005, 12(6): 28-30
[5] Yu R P, Chen D M. The utilzation and exploitation of saline soil resources in China[J]. Chinese Journal of Soil Science, 1999, 30(4): 158-159
[6] Liu X J, Li X J, Chen L N, et al. Discussion on adaptive farming system in saline soils—A case study in saline area of strand plain in Hebei Province[J]. Chinese Journal of Eco-Agriculture, 2010, 18(4): 911-913
[7] Niu D L, Wang Q J. Research progress on saline-alkali field control[J]. Chinese Journal of Soil Science, 2002, 33(6): 449-455

[8] Liu Y C, An X R, Yang L H. Potential analysis of brackish water utilization in Hebei[J]. Water Science and Engineering Technique, 2006(1): 13-15

[9] Wang W G, Zhang R D, Wang X G. Water and salt transport on saline water irrigation[J]. Journal of Irrigation and Drainage, 2004, 23(3): 1-4

[10] Pang H C, Yang J S, Yan H J. Effect of irrigation with saline water on soil salinity and crop yield[J]. Plant Nutrition and Fertilizer Science, 2004, 10(6): 599-603

[11] Li Z G, Liu X J, Zhang X M, et al. Infiltration of melting saline ice water in soil columns: Consequences on soil moisture and salt content[J]. Agricultural Water Management, 2008, 95(4): 498-502

[12] Guo K, Zhang X M, Li X J, et al. Effect of freezing saline water irrigation in winter on the reclamation of coastal saline soil[J]. Resources Science, 2010, 32(3): 431-435

[13] Li Z G, Liu X J, Zhang X M, et al. Infiltration of melting saline ice water in soil columns: Consequences on soil moisture and salt content[J]. Agricultural Water Management, 2008, 95(4): 498-502

[14] Zhang D F, Wang S J. Mechanism of freeze-thaw action in the process of soil salinization in northeast China[J]. Environmental Geology, 2001, 41(1/2): 96-100

[15] Zhang D F, Zheng Q H, Dong Z Y, et al. Mechanism of soil salt-moisture transfer under freeze-thawing condition[J]. Bulletin of Soil and Water Conservation, 2005, 25(6): 14-18

[16] Zhang D F, Zheng Q H. Simulation of water-salt movement law under the freeze-thawing condition[J]. Progress in Geography, 2005, 24(4): 46-55

[17] Qadir M, Oster J D. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture[J]. Science of the Total Environment, 2004, 323(1/3): 1-19

[18] Oster J D. Irrigation with poor quality water[J]. Agricultural Water Management, 1994, 25(3): 271-297

[19] Wang Q J, Xu Y M, Wang J D, et al. Application of saline and slight saline water for farmland irrigation[J]. Irrigation and Drainage, 2002, 21(4): 73-78

[20] Bauder J W, Brock T A. Irrigation water quality, soil amendment, and crop effects on sodium leaching[J]. Arid Land Research and Management, 2001, 15(2): 101-113

[21] Ma D H, Wang Q J, Su Y, et al. Analysis of the characteristics of soil water and salt movement in saline water infiltration[J]. Journal of Irrigation and Drainage, 2006, 25(1): 62-66

[22] Xiao Z H, Wan H F. Effect of irrigation water quality on soil hydraulic and physical properties[J]. Acta Pedologica Sinica, 1998, 35(3): 359-366

[23] Su Y, Wang Q J, Ye H Y, et al. Study on water and salt transporting feature of soil with different infiltration amount of saline water[J]. Agricultural Research in the Arid Areas, 2005, 23(4): 43-48

[24] Tedeschi A, Dell' Aquila R. Effects of irrigation with saline waters, at different concentrations, on soil physical and chemical characteristics[J]. Agricultural Water Management, 2005, 77(1/3): 308-322

[25] Suarez D L, Wood J D, Lesch S M. Effect of SAR on water infiltration

under a sequential rain-irrigation management system[J]. Agricultural Water Management, 2006, 86(1/2): 150-164

[26] Li J, Cao C Y, Zheng C L, et al. Salinity threshold of long-term saline water irrigation for winter wheat in Hebei Lowland Plain[J]. Chinese Journal of Eco-Agriculture, 2016, 24(5): 643-651

[27] Shi P J, Ha S, Yuan Y, et al. The desalinization of Bohai sea ice and it us value as fresh water resources[J]. Journal of Natural Resources, 2002, 17(3): 353-360

[28] Khawaji A D, Kutubkhanah I K, Wie J M. Advances in seawater desalination technologies[J]. Desalination, 2008, 221(1/3): 47-69

[29] Williams P M, Ahmad M, Connolly B S. Freeze desalination: An assessment of an ice maker machine for desalting brines[J]. Desalination, 2013, 308: 219-224

[30] Nakagawa K, Maebashi S, Maeda K. Freeze-thawing as a path to concentrate aqueous solution[J]. Separation and Purification Technology, 2010, 73(3): 403-408

[31] Wang X B, Zhao Q S, Hu Y J, et al. An alternative water source and combined agronomic practices for cotton irrigation in coastal saline soils[J]. Irrigation Science, 2011, 30(3): 537-546

[32] Luo C S, Chen W W, Han W F. Desalination of brackish water through freezing[J]. Journal of Lanzhou University: Natural Sciences, 2010, 46(2): 6-10

[33] Beier N, Sego D, Donahue R, et al. Laboratory investigation on freeze separation of saline mine waste water[J]. Cold Regions Science and Technology, 2007, 48(3): 239-247

[34] Guo K, Liu X J. The primary research on the variation of melted water quality and quantity during saline ice melting[J]. Journal of Irrigation and Drainage, 2013, 32(1): 56-60

[35] Guo K, Liu X J. Infiltration of meltwater from frozen saline water located on the soil can result in reclamation of a coastal saline soil[J]. Irrigation Science, 2015, 33(6): 441-452

[36] Feng X H, Zhang X M, Guo K, et al. Effects of different salt control measures after saline water freezing irrigation to soil water, salt dynamics, cotton emergence and yield[J]. Cotton Science, 2015, 27(2): 135-142

[37] Guo K, Chen L N, Zhang X M, et al. Water and salt distribution in coastal saline soil after infiltration of meltwater of saline water ice with different sodium adsorption ratio[J]. Chinese Journal of Eco-Agriculture, 2011, 19(3): 506-510

[38] Pan J, Xiao H, Wang L Y, et al. Study on migration of different salt ions in melting and infiltration processes of saline water ice[J]. Acta Agriculturae Boreali-Sinica, 2012, 27(1): 210-214

[39] Che S G, Lin Z A, Zhao B Q, et al. Effects of agricultural irrigation by melting saline water ice on soil salt and ion movement under fluvo-aquic soils[J]. Journal of Soil and Water Conservation, 2011, 25(4): 88-93

[40] Guo K, Zhang X M, Li X J. Effect of the water and salt transport on soda alkaline soil after infiltration with melting ice saline water of different SAR[J]. Journal of Soil and Water Conservation, 2010, 24(4): 94-98

[41] Guo K, Liu X J. Dynamics of meltwater quality and quantity during saline

ice melting and its effects on the infiltration and desalinization of coastal saline soils[J]. Agricultural Water Management, 2014, 139: 1-6
[42] Yang F, Wang Z C, Xiao Y. Effect of freezing water irrigation on the changes of soilwater and salt in saline-sodic soil area[J]. Scientia Geographica Sinica, 2012, 32(10): 1241-1246

Note: Figure translations are in progress. See original paper for figures.