ChinaRxiv 中X

AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202206.00008

Spatial Variation Characteristics of Soil Salinization and Its Primary Controlling Factors in Western Hetao Irrigation District (Postprint)

Authors: Su Chunli

Date: 2022-06-02T00:00:00+00:00

Abstract

Due to long-term Yellow River water diversion for irrigation, extensive secondary salinization has occurred in the soils of the Hetao Irrigation District, seriously impacting the sustainable development of the regional economy and ecology. Through systematic investigation and analysis of the current status of soil salinization in Linhe District, western Hetao Irrigation District, this study identified the degree, types, and distribution characteristics of soil salinization within the study area and discussed the main influencing factors and causes of regional soil salinization. The results indicate that: (1) Over 50% of the soils in the study area have undergone varying degrees of secondary salinization, exhibiting a patchy distribution pattern; soil salinization is more severe in the northern and southeastern regions, particularly in the low-lying areas along both sides of the Zonggan Canal and Huangji Canal; the primary salt types in the soils are SO4-Na and SO4 · Cl-Na. (2) The average total dissolved solids (TDS) content of shallow groundwater in the study area is 2.13 g · L-1, classifying it as brackish water, with an average water table depth of 4.65 m, and 65% of the survey points having depths less than 3 m. (3) The direct causes of high-TDS groundwater formation are the rise in groundwater level and strong evaporation-concentration effects induced by long-term surface flood irrigation and winter salt leaching practices, while the main controlling factors of soil salinization in the alluvial plain are the upward movement of salts driven by higher groundwater salinity, shallow groundwater table rise, and strong phreatic evaporation.

Full Text

Differentiation Characteristics and Main Influencing Factors of Soil Salinization in the West of Hetao Irrigation Area

SU Chunli[12], JI Qiannan[12], TAO Yanzhen[12], XIE Xianjun[12], PAN Hongjie[3]

[1] School of Environmental Studies, China University of Geosciences, Wuhan, Hubei 430074, China
[2] State Environmental Protection Key Laboratory of Water Pollution Tracing and Control, Wuhan, Hubei, China
[3] Geological Survey Institute of Inner Mongolia, Hohhot 010020, Inner Mongolia, China

Abstract

Due to long-term Yellow River water irrigation, the Hetao Irrigation Area has experienced extensive secondary soil salinization, which seriously impedes regional economic and ecological development. Through systematic investigation and analysis of soil salinization status in Linhe District, western Hetao Irrigation Area, this study identified the degree, types, and distribution characteristics of soil salinization, and examined the main influencing factors and formation mechanisms. Results indicate that over 50% of soils in the study area have undergone varying degrees of secondary salinization, distributed in a patchy pattern. Soil salinization is particularly severe in the northern and southeastern regions, especially in depressions along the Main Canal and Huangji Canal. The primary salt types are $SO_4 \cdot$Cl-Na. The shallow groundwater in the study area has an average total dissolved solids (TDS) content of 2.13 $g \cdot L^{-1}$, classifying it as brackish water, with an average water table depth of 4.65 m. Long-term surface flood irrigation and winter salt-leaching practices cause groundwater level rise and intense evaporation concentration, which directly lead to high-TDS groundwater. Elevated groundwater salinity, shallow water tables, and strong phreatic evaporation constitute the main controlling factors for soil salinization in the alluvial plain.

Keywords: soil salinization; groundwater level; salt content; formation mechanism; flood irrigation; Hetao Irrigation Area

Introduction

Soil salinization represents a widespread environmental problem that reduces land productivity, causes farmland degradation, and leads to loss of arable land, contributing significantly to global food shortages. It is estimated that over 50% of arable land may become salinized by 2050, with most occurring in arid and semi-arid regions. The Hetao Irrigation Area, a typical arid/semi-arid region in

China, serves as an important commodity base for grain, oil, and sugar production in Inner Mongolia and nationwide. However, due to scarce rainfall, intense evaporation, high salt content in soil parent material, and elevated groundwater levels, secondary soil salinization poses particularly prominent threats to agricultural production and economic development in this region.

Surface soil salt conditions and salinization degree during dry seasons reflect the final outcome of salt accumulation and migration processes in surface soils, representing a critical interface between soil systems and water flow that contains extensive information on ion chelation and water movement. Under natural conditions, groundwater level and quality are considered key determinants of soil salinization on flat terrain, as groundwater serves as the primary geological agent for salt transport, accumulation, and discharge. Secondary soil salinization results from salt migration and accumulation in soil profiles caused by additional water input from human activities such as irrigation. This study investigates soil salinization status in western Hetao Irrigation Area to identify salinization degree, genetic types, and distribution characteristics, discuss main controlling factors, and develop a salinization formation model for the Hetao region, providing insights for salinization prevention in arid/semi-arid areas.

1. Study Area Overview

The study area is located in central Bayannur City, Inner Mongolia, within the heart of Hetao Plain, spanning 40°33 16 -41°16 31 N and 107°06 13 -107°43 40 E. It covers regions surrounding the Third Drainage Canal, Huangji Canal, Fourth Drainage Canal, and Yongji Canal in the Hetao Irrigation Area, bordering the Ordos Plateau across the Yellow River to the south and backed by the Yinshan Mountains to the north, with a total area of approximately 2212 km^2.

The region belongs to a continental arid/semi-arid climate zone characterized by scarce precipitation, intense evaporation, cold winters, hot summers, dry and windy springs, and large diurnal temperature variations. The multi-year average precipitation is 100–400 mm, while annual evaporation reaches 2000–2400 mm. Elevation ranges from 1021 to 1046 m, with higher terrain in the southwest and lower in the northeast. The surface slope decreases from 0.025% to 0.0125%, resulting in poor surface runoff and sluggish subsurface flow. The Yellow River passes along the southern edge of the irrigation area at a relatively high topographic position, with groundwater flow direction generally consistent with surface slope.

Long-term large-scale Yellow River water irrigation has created significant groundwater recharge, resulting in shallow water tables and strong evaporation in some low-lying areas with high soil salt accumulation. Soil texture varies from loamy to clay loam with well-developed capillaries. Due to the arid climate and intense evaporation, water and salts migrate to the surface through capillary action, exacerbating soil salinization problems in the irrigation area.

Currently, Bayannur City has 715,200 hm^2 of arable land, of which approximately 322,667 hm^2 (45.1%) is salinized to varying degrees. Light to moderate saline-alkali land is primarily planted with salt-tolerant crops such as sunflowers, while severely salinized land can only support sparse alkaline grasses with no economic value.

2. Materials and Methods

In October 2020, 93 surface soil samples (0–20 cm tillage layer) and 47 groundwater samples were uniformly collected across the study area. Soil sampling sites included both wasteland and cultivated land, covering areas with varying salinization degrees. Sampling locations are shown in [Figure 2: see original paper]. Soil samples were obtained by mixing five subsamples using the quartering method. During sampling, soil condition, lithology, coordinates, and surrounding environmental conditions were recorded, with samples stored to prevent cross-contamination.

All soil samples were air-dried, ground, and sieved through a 2 mm mesh. Soil salinity was measured using a 1:5 soil-water ratio extraction and filtration method. Soil pH and electrical conductivity (EC) were measured using a HACH HQ · 40d multi-parameter meter, while total salt content was determined using a combination of conductivity and gravimetric methods. Groundwater temperature, pH, and alkalinity were measured on-site using the HACH HQ · 40d portable multi-parameter meter, with alkalinity determined by titration. Water samples were filtered through 0.45 m mixed cellulose ester membranes for major anion and cation analysis. For cation analysis, samples were acidified with ultrapure concentrated nitric acid. Major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, ${SO_4}^{2-}$, ${HCO_3}^-$) were analyzed using a Metrohm 761 Compact IC. All analyses were completed at the State Key Laboratory of Biogeology and Environmental Geology and the Environmental School Experimental Center, China University of Geosciences (Wuhan).

3. Results and Analysis

3.1 Soil Salinization Degree and Type

Analysis of soil extract pH, EC, and salt content revealed that pH ranged from 6.61 to 10.08, indicating strongly alkaline surface soils. Soil salinization degree varied considerably, with salt content ranging from 0.02% to 4.27%. According to soil salinization classification standards (Table 1), over 50% of soils experienced salinization. Specifically, lightly salinized soils accounted for 21.7%, moderately salinized soils for 12.4%, heavily salinized soils for 8.53%, and saline or alkaline soils for 10.08% (Table 2).

To further determine salinization types, 12 representative soil samples were analyzed for major ions. Results showed average anion contents in surface soils followed the order: ${SO_4}^{2-} > Cl^- > {HCO_3}^-$, while cation contents followed: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. The dominant salt type was SO_4 · Cl-Na. The average sodium adsorption ratio (SAR) was 2.94, indicating low soil alkalinization. The average soluble sodium percentage (SSP) was 56.28%, showing Na^+ as the dominant cation with high soil sodification. The average $Na^+/Ca^{2+}+Mg^{2+}$ ratio was 1.52, further confirming high sodification degree.

3.2 Spatial Distribution Characteristics of Soil Salinity

Using ArcGIS geostatistical tools, spatial interpolation of surface soil salt content in Linhe District was performed to map salinity distribution. Heavy saline soils and saline soils were mainly distributed in low-lying areas along both sides of the Main Canal and Huangji Canal, following the pattern of "salts accumulate in depressions, lighter accumulation on slopes," with patchy distribution. Overall, soil salinization was more severe in the northern and southeastern parts of the study area, with Manhui Town, northern Bainaobao Town, southeastern Hanggin Rear Banner, and Shuanghe Town being primary distribution zones for saline and heavy saline soils.

In contrast, soil salt content in areas along the upper reaches of the Fourth Drainage Canal, northern Bayi and Badai Townships, Nanqu Township, and Ganzhaomiao Town was 0.2–1.0%, indicating lighter salinization.

3.3 Influencing Factors of Soil Salinization

Major influencing factors include groundwater level, groundwater salinity, irrigation methods, and phreatic evaporation. Secondary factors such as plant transpiration, water-rock interaction, and salt dissolution in the unsaturated zone from irrigation infiltration also contribute.

3.3.1 Groundwater Level and Salinity Groundwater depth in the study area ranged from 0.65 to 6.21 m, with an average of 4.65 m. At 64.9% of sampling points, depth was less than 3 m, primarily distributed in front of the Langshan Mountains. Groundwater TDS ranged from 0.69 to 10.89 $g \cdot L^{-1}$, averaging 2.13 $g \cdot L^{-1}$, classifying it as brackish water with weak alkalinity (pH 7.23–8.45). The main hydrochemical types were $Cl \cdot SO_4 \cdot HCO_3$-$Na \cdot Ca \cdot Mg$ and $Cl \cdot HCO_3$-$Na \cdot Mg$ types.

Comparison of spatial distributions reveals that areas with moderate to severe soil salinization correspond to shallow groundwater depths (generally <3 m). When water tables are below the critical depth (the minimum depth that prevents serious salt accumulation and crop damage), salts migrate upward to the tillage layer and surface through capillary action. The critical depth is approximately 1.8–2.2 m for sandy soils and 1.0–1.5 m for clayey soils in Hetao Irrigation Area. In low-lying areas with shallow water tables, strong evaporation leaves salts in the soil, causing salinization.

The relationship between groundwater depth and TDS shows that shallow groundwater (<3 m) has elevated TDS, while some deep groundwater also exhibits high TDS, possibly due to hydraulic connections with shallow aquifers causing vertical leakage. Grey correlation analysis between groundwater depth, TDS, and surface soil salt content yields correlation coefficients of 0.65 and 0.71, respectively, indicating significant influence on soil salinization.

Previous hydrochemical and hydrogen-oxygen isotopic analysis of shallow groundwater revealed that the evaporation line slope (δD = 4.8δ^{18}O-28.2) is lower than the local meteoric water line (δD = 7.6δ^{18}O-4.07), demonstrating significant evaporation concentration effects on groundwater.

3.3.2 Agricultural Irrigation and Evaporation Irrigation has dual effects on soil salinization. During irrigation, surface-accumulated salts can leach into deeper soil or aquifers. However, in areas with shallow water tables, continuous groundwater evaporation concentrates salts locally, forming extremely high-TDS groundwater. Under strong evaporation, salts migrate upward with groundwater and accumulate at the surface, inducing secondary salinization.

In the semi-arid study area with annual evaporation of 2000–2400 mm, intense evaporation creates a massive evaporation field. Phreatic evaporation is a key natural force accelerating secondary salinization. In low-lying areas with shallow water tables, continuous phreatic water convergence and evaporation discharge lead to groundwater concentration and high TDS. Plant transpiration also contributes to shallow groundwater discharge in agricultural regions.

3.4 Formation Mechanism of Soil Salinization

Hetao Plain is an agricultural region primarily irrigated with Yellow River water. During irrigation, large amounts of return flow infiltrate, and massive winter salt-leaching irrigation occurs annually. This leaches unsaturated zone salts into groundwater, increasing groundwater salinity while raising water tables and hydraulic gradients, thereby intensifying groundwater circulation.

Natural factors include large temperature variations, scarce precipitation, and strong evaporation, combined with generally shallow phreatic depths ($<$3 m), creating extensive evaporation fields. Long-term intense evaporation causes salts from deep soils and shallow groundwater to accumulate at the surface through capillary action, leading to salinization.

Anthropogenic factors include long-term flood irrigation that raises water tables, promoting increased phreatic evaporation and upward salt movement. Hetao Irrigation Area uses flood irrigation with Yellow River water, applying approximately 5.0$\times10^{9}$ m^3 annually (reduced to about 4.0$\times10^{9}$ m^3 in recent years due to water conservation measures), including three crop growth-stage irrigations and one autumn irrigation for salt leaching and moisture conservation. This infiltration of irrigation return water gradually raises water tables, while poor lateral runoff leads to insufficient drainage.

The geological setting and climate determine that the water cycle process in the irrigation area is irrigation (rainfall)-phreatic evaporation type. Under strong phreatic evaporation and plant transpiration, salts in groundwater migrate to the soil surface and accumulate, causing secondary salinization. The annual salt input from Yellow River water irrigation is approximately 2.80$×10^{8}$ kg, with 1.20$×10^{{8}−1.50×10}{8}$ kg accumulating annually.

In summary, long-term flood irrigation and salt-leaching-induced water table rise with intense evaporation concentration directly cause high-TDS groundwater, while high-salinity groundwater, shallow water tables, and strong phreatic evaporation are the main factors controlling alluvial plain soil salinization.

A conceptual model of soil salinization formation is illustrated in [Figure 7: see original paper].

4. Conclusions

1) Soil salinization degree in the study area varies considerably, with salt content ranging from 0.02% to 4.27%. The main salt type is $SO_4 \cdot Cl$-Na. Lightly salinized soils account for 21.7%, moderately salinized soils for 12.4%, heavily salinized soils for 8.53%, and saline or alkaline soils for 10.08%.

2) Heavy saline soils and saline soils are mainly distributed in low-lying areas along both sides of the Main Canal and Huangji Canal, particularly in middle and lower reaches, following the pattern of "salts accumulate in depressions, lighter accumulation on slopes."Soil salinization is more severe in the northern and southeastern regions, with Manhui Town, northern Bainaobao Town, southeastern Hanggin Rear Banner, and Shuanghe Town being primary distribution zones.

3) Shallow groundwater in the study area has an average TDS of 2.13 $g \cdot L^{-1}$ (brackish water), weak alkalinity, and main hydrochemical types of $Cl \cdot HCO_3$-Na and $Cl \cdot SO_4 \cdot HCO_3$-$Na \cdot Ca \cdot Mg$ types. The average water table depth is 4.65 m, with 64.9% of sampling points shallower than 3 m.

4) Long-term flood irrigation and winter salt-leaching cause groundwater level rise and intense evaporation concentration, directly leading to high-TDS groundwater. Elevated groundwater salinity, shallow water tables, and strong phreatic evaporation are the main factors affecting alluvial plain soil salinization. Large amounts of irrigation return water leach unsaturated zone salts into groundwater, increasing salinity and water tables while intensifying groundwater circulation. High-salinity groundwater from the riverbank zone flows northward into the alluvial plain, increasing salinity in front-edge areas and promoting water-rock interaction. Lateral recharge from the Langshan Mountains front and irrigation infiltration further raise water tables in the alluvial plain, causing secondary soil salinization under strong groundwater evaporation and plant transpiration.

References

[1] Tefera B, Sterk G. Land management, erosion problems and soil and water conservation in Fincha watershed, western Ethiopia [J]. Land Use Policy, 2010, 27(4): 1027-1037.

[2] Shrivastava P, Kumar R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation[J]. Saudi Journal of Biological Sciences, 2015, 22(2): 123-132.

[3] Wu J, Li P, Qian H, et al. Assessment of soil salinization based on a low cost method and its influencing factors in a semi arid agricultural area, Northwest China[J]. Environmental Earth Sciences, 2014, 71(8): 3465-3475.

[4] Pitman M G, André Luchli. Global Impact of Salinity and Agricultural Ecosystems[M]. Salinity: Environment Molecules, Plants, Springer Netherlands, 2004.

[5] Jiang Guirong, Liu Yanfeng, Yang Xiaoyi, et al. Spatial variability and stochastic simulation of soil salinity in the vertical profiles of arid areas[J]. Geological Science and Technology Information, 2013, 32(2): 147-152.

[6] Wang Jiali, Huang Xianjin, Zhong Taiyang, et al. Review on sustainable utilization of salt affected land[J]. Acta Geographica Sinica, 2011, 66(5): 673-684.

[7] Vinocur B, Altman A. Recent advances in engineering plant tolerance to abiotic stress: Achievements and limitations[J]. Current Opinion in Biotechnology, 2005, 16(2): 123-132.

[8] Wang Y, Li Y, Xiao D. Catchment scale spatial variability of soil salt content in agricultural oasis, Northwest China[J]. Environmental Geology, 2008, 56(2): 439-446.

[9] Dou Xu, Shi Haibin, Miao Qingfeng, et al. Temporal and spatial variability analysis of soil water and salt and the influence of groundwater depth on salt in saline irrigation area[J]. Journal of Soil and Water Conservation, 2019, 33(3): 246-253.

[10] Guan Xiaoyan, Wang Shaoli, Gao Zhanyi, et al. Spatiotemporal variability of soil salinity and its relationship with the depth to groundwater in salinization irrigation district[J]. Acta Ecologica Sinica, 2012, 32(4): 1202-1210.

[11] Zhou Zaiming, Zhao Shuhui. Influencing factors on surface soil salt accumulation in the semi arid North China Plain[J]. Arid Land Geography, 2015, 38(5): 976-984.

[12] Liu H, Chen W, Dong X, et al. Sustainable agricultural paradigm of mountain oasis ecotone desert system in inland Manas River Basin, Xinjiang Province, northwest China[C]//International Conference on Computer and Computing Technologies in Agriculture. Springer, Boston, MA, 2008: 197-207.

[13] Fan X, Pedroli B, Liu G, et al. Soil salinity development in the Yellow River Delta in relation to groundwater dynamics[J]. Land Degradation & Development, 2012, 23(2): 175-189.

[14] Shi Haibin, Yang Shuqing, Li Ruiping, et al. Soil water and salt movement and soil salinization control in Hetao Irrigation District: Current state and future prospect[J]. Journal of Irrigation and Drainage, 2020, 39(8): 1-17.

[15] Yu R, Liu T, Xu Y, et al. Analysis of salinization dynamics by remote sensing in Hetao Irrigation District of North China[J]. Agricultural Water Management, 2010, 97(12): 1952-1960.

[16] Jing Yupeng, Duan Yu, Tuo Debao, et al. Characteristics of salinization of deserted farmland in Hetao Plain[J]. Acta Pedologica Sinica, 2016, 53(6): 1410-1420.

[17] Zeng Hanbin, Su Chunli, Xie Xianjun, et al. Mechanism of salinization of shallow groundwater in western Hetao Irrigation Area[J]. Earth Science, 2021, 46(6): 2267-2277.

[18] Wang J, Liu Y, Wang S, et al. Spatial distribution of soil salinity and potential implications for soil management in the Manas River watershed, China[J]. Soil Use and Management, 2020, 36(1): 93-103.

[19] Zhou Liying, Li Ruiping, Miao Qingfeng, et al. Characteristics of salinization and fertility of saline alkali soil adjacent to drainage ditch in Hetao irrigation area of Inner Mongolia[J]. Arid Zone Research, 2021, 38(1): 114-122.

[20] Ma Guiren, Qu Zhongyi, Wang Liping, et al. Research on soil water and salt movement and groundwater dynamics in Hetao Irrigation District based on ArcGIS spatial interpolation[J]. Journal of Soil and Water Conservation, 2021, 35(4): 208-215.

[21] Tarchouna L G, Merdy P, Raynaud M, et al. Effects of long term irrigation with treated wastewater. Part I: Evolution of soil physico chemical properties[J]. Applied Geochemistry, 2010, 25(11): 1703-1710.

[22] Liu Jun, Guo Hualiang, Liu Fuliang, et al. The variations of stable isotopes (δD and δ^{18}O) in the precipitation in Baotou area[J]. Journal of Arid Land Resources and Environment, 2013, 27(5): 157-162.

[23] Du Jun, Yang Peiling, Li Yunkai, et al. Analysis of spatial and temporal variations of groundwater level and its salinity in Hetao Irrigation District[J]. Transactions of the CSAE, 2010, 26(7): 26-31.

[24] Liu Mei, Yu Dongyang, Liu Yujie, et al. Saline alkali soil status and improvement measures of Hanggin Rear Banner[J]. Journal of Northern Agriculture, 2017, 45(3): 58-61.

[25] Cui Yali, Shao Jingli, Han Shuangping. Ecological environment adjustment by groundwater in Northwest China[J]. Earth Science Frontiers, 2001, 8(1): 192-197.

[26] Wang Baofang, Yang Xiaohui, Jiang Zeping. Utilization of water resources and soil salinization control in the Dengkou Irrigated Area Inner Mongolia[J]. Arid Zone Research, 2004, 21(2): 139-143.

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

Source: ChinaXiv —Machine translation. Verify with original.