Soil salinity patterns reveal changes in the water cycle of inland river basins in arid zones

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Abstract: Soil salinization caused by irrational water resource use seriously affects the agricultural development and ecological construction of inland river basins in arid zones, so clarifying the water cycle mechanism of salinization in inland river basins in arid zones is crucial for the ecological environment management of the basins and the rational use of water resources. Based on remote sensing and observation data, this study quantitatively analyzed the changes in soil salinity in the Shiyang River Basin from 2002 to 2022. It explored the impacts of water conservancy projects, farmland irrigation, and climate change on soil salinity. The results of the study show that: (1) the salinized area in the Shiyang River Basin is generally on the rise, and the degree of salinization is further aggravated; (2) the lower reaches of the Shiyang River are the areas with more severe salinization, and the middle and upper reaches of the river are at lesser risk of salinization; and (3) the regional salinization problem is more prominent as a result of the rise in the groundwater level around the reservoirs, the evaporation from the irrigation of the agricultural fields, and the evaporation from the downstream ecological water conveyance. Human activities have become a decisive factor in changing the salinization pattern of inland river basins, and the rational use and management of water resources have great potential to improve soil salinization.
Keywords: arid zones; soil salinization; reservoirs; water transfer projects

1. Introduction

Land is an essential natural resource for human beings with economic, social, and ecological benefits in various production activities (Lambin and Meyfroidt., 2011). Soil is the basis of natural ecosystems. Material and energy can cycle within the system and interact with the biosphere, hydrosphere, atmosphere, and so on. Soils can promote plant growth and coordinate the watershed water cycle by regulating infiltration and distribution of precipitation. The purification capacity of soils breaks down potential pollutants, preventing water and air pollution to some extent (Bünemann et al., 2018). At the same time, water bodies also impact soil quality, mainly through irrigation and precipitation, which influence changes in soil composition. Once soil quality decreases or degrades, it will cause irreversible damage and directly affect human life. Soil salinization is critical to land degradation (Daliakopoulos et al., 2016). It specifically means that water is lost after groundwater rises to the surface through evaporation from soil pores to the atmosphere under high temperatures. At the same time, heavy masses of salts remain at the surface as they precipitate. Long-term accumulation of salts at the soil surface affects the growth of all types of crops, which can lead to negative consequences such as reduced yields (Folberth et al., 2016). Soil salinization can be divided into primary and secondary salinization according to the cause of its formation. Primary salinization is mainly influenced by natural factors such as physical or chemical interaction of rocks during the water cycle, sea level rise leading to erosion of coastal land, infiltration of sedimentary brine, evaporation from sea level, changes in the composition of the soil colony, and atmospheric precipitation, all of which increase the salt concentration in the groundwater, resulting in widespread soil salinization (Kaushal et al., 2005; Zhuang et al., 2021; Perri et al., 2022).

The problem of secondary salinization of soil triggered by human activities and incredibly irrational agricultural irrigation has increased the risk of elevated salt concentrations in groundwater. It has become a challenge in areas such as hydrology and agriculture. Artificial water transfer projects have significantly altered the connectivity between groundwater and soil water, and the trend of salt enrichment to the surface through evaporation has become more pronounced. Seasonal storage in reservoirs also affects soil water salinity in watersheds. The global area of saline soils is estimated to have exceeded 833 million hectares (Food and Agriculture Organization of the United Nations). Globally, about 20 percent of agricultural land and 33 percent of irrigated agricultural land is saline (Xiao et al., 2023), which is expected to worsen (Hassani et al., 2021). In the inland river basins of the arid zone, the climate is exceptionally arid, the intensity of evaporation from soils and plants is high, and the water table is high. As a result, soil salinization in arid and semi-arid regions is more severe and more extensive, with salinized cultivated land in the inland northwest accounting for nearly one-fifth of the total cultivated land in China; therefore, the study of soil salinization in inland river basins in the arid zone is conducive to the understanding of water cycle processes and mechanisms in the basins and is of great significance in irrigated agriculture and water resource management (Wei et al., 2020).

Remote sensing technology has been widely used to assess soil salinization, and feature spectral characteristics are essential markers for identifying saline soils (Konstantin et al., 2019). Saline soils show absorption peaks in the visible band, and there is a positive correlation between their soil reflectance and soil salinity. In world-scale soil salinity studies, researchers have used machine learning methods to monitor the dynamics of soil surface salinity over the past four decades (Hassani et al., 2020) and ML algorithms to predict soil salinity in the 21st century in the context of global climate change (Has-sani et al., 2021). It was found that the salt-affected areas were mainly distributed in arid and semi-arid regions, significantly more severe in northwestern China. The risk challenge of soil salinization is further increased in arid and semi-arid regions of China due to their special climatic conditions, which are influenced by irrigation, drainage, and ecological water transport (Wang et al., 2012; Miguel et al., 2013).

Assessing the distribution of soil salinity in a watershed is critical to understanding how natural and human activities affect soil salinity in arid zones. In this study, we proposed to address the following issues using multi-source data: (1)

quantify the extent of salinization in the Shiyang River Basin; (2) analyze the impacts of water cycle changes on salinization. The study's results will help clarify the impact of the water cycle on soil salinization in the inland river basin and provide a scientific basis for agricultural development, ecological construction, and water resource use planning in the arid zone.

2. Materials and Methods

2.1 The Background Conditions of the Study Area

The Shiyang River Basin is located in northwestern China, at the eastern end of the Hexi Corridor. It consists of eight major tributaries: the Dajing River, the Gulang River, the Huangyang River, the Zaomu River, the Jinta River, and the Xiyang River. Lakes and wetlands in the whole region mainly exist in reservoirs, with 15 reservoirs built with a more than 1 million cubic meters capacity. Water storage in reservoirs helps to adjust the distribution of river water and improve the ecological environment in the northwest. The study area has a continental temperate arid climate with high solar radiation intensity, scanty precipitation (average annual precipitation is 200-300mm), intense evaporation, and a significant temperature difference between morning and evening, and the degree of aridity in the study area gradually increases from south to north. The geomorphological features are apparent, and the terrain is tilted from southwest to northeast, which can be divided into four geomorphological units: the southern Qilian Mountains, the central corridor plains, the northern low hills, and the desert area. Soil types vary significantly from north to south, with higher altitudes in the south. Soil types include alpine cold desert soil, alpine meadow soil, forest grey-brown soil, mountain grassland, and arid grassland soil. The base zone in front of the Qilian Mountains is primarily a transitional semi-desert zone. The climate in the north is gradually arid, with prominent desert characteristics, and the soil types are mainly desert grey-calcium soil and grey-brown desert soil.

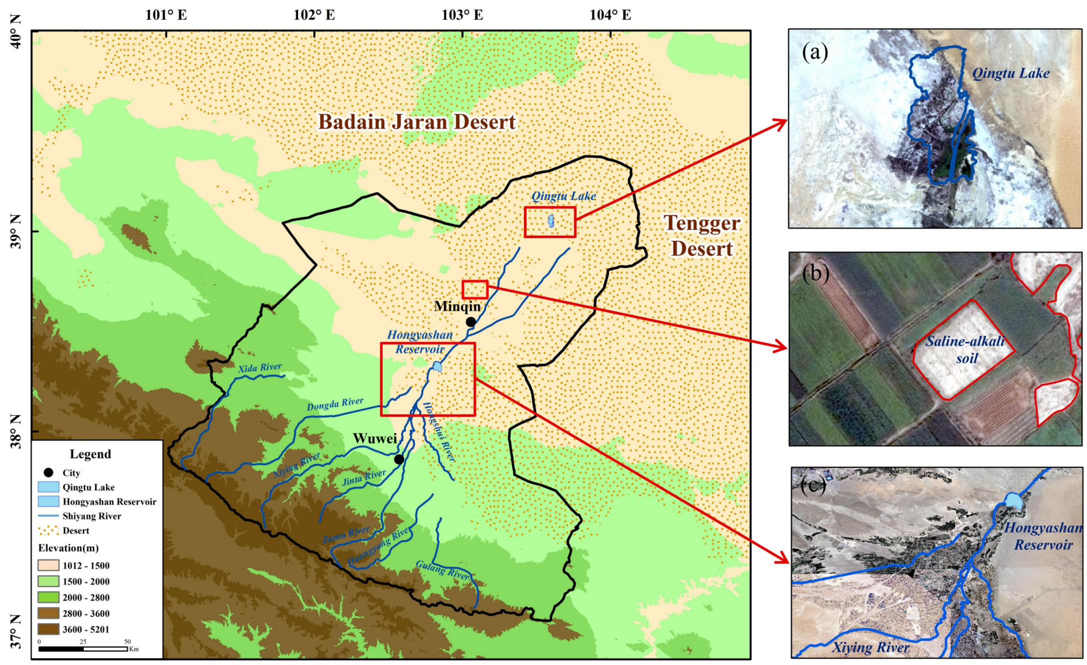

Figure 1. Overview map of the study area(a: Qingtu Lake(from USGS); b: Saline soils in agricultural land (from © Google Maps); c: Distribution of water systems in the Shiyang River Basin(from USGS))

2.2 Data

The U.S. Landsat (Landsat) series, jointly managed by the National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey (USGS), is a series of U.S. Earth-observing satellite systems used to explore the Earth's resources and environment. Landsat is primarily used to investigate marine and groundwater resources and to help regulate the rational use of water resources (National Research Council., 1997). Landsat data are derived from the Earth Explorer service (https://earthxplorer.usgs.gov), which provides surface reflectivity every 16 days with a spatial resolution of 30 meters.

This paper uses satellite data from Landsat-5, Landsat-7, Landsat-8, and Landsat-9. Landsat-5 was launched in March 1984, which carries the Multi-spectral Scanner (MSS) and the Thematic Mapper (TM) and provides nearly 29 years of Earth imaging data.Landsat-7 was launched in 1999. Launched in April, the satellite carries the Enhanced Thematic Mapper (ETM+) and the SLC sensor. Since June 2003, the sensor has acquired and transmitted data from data gaps caused by scan line corrector

(SLC) failures, providing improved radiometric and geometric data.Landsat-8, launched in February 2013, carries the Ordnance Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), which guarantees continuity in the reception and availability of terrestrial data, which is comparable to the standard Landsat data products available. The OLI sensor acquires remote sensing images in the visible, near-infrared, and short-wave infrared wavelength ranges. It is designed with a push-scan structure that gives it better grade stability and image quality.Landsat-9 carries the OLI-2 sensor, which has a higher radiometric resolution, allowing for more subtle detection of areas such as water and dense forests. Detect more subtleties.

2.3 Data preparation and processing

Landsat series satellites have multispectral and panchromatic data; the resolution of multispectral data is 30m, and the resolution of the panchromatic band is 15m. At the same time, a 30m Shiyang River Basin land use data product for the period 2002-2022 was obtained, which is available in the public domain(https://doi.org/10.5281/zenodo.4417810)(Yang & Huang, 2022). In this paper, 2002, 2007, 2012, 2017, and 2022 were selected as the study periods, and 4-scene images were selected for each period to cover the whole study area. Priority was given to downloading high-quality remote sensing images in summer each year with cloudiness of less than 1%, which was more conducive to identifying the salinity degree of the soil. In order to improve the image quality to meet the later remote sensing salinity inversion, it is necessary to pre-process the images in ENVI software in the early stage, including radiometric calibration, atmospheric correction, image fusion, image mosaicing, and image cropping steps. In addition, DEM (Digital Elevation Model) data at 30m resolution and Slope (slope) data of the study area were extracted through GIS as auxiliary data. The data processing flow is shown in Figure 2.

Significant differences exist between the reflectance of various soil salinities in the spectral features (visible and near-infrared (NIR). In the spectral region, saline soils have higher reflectance than non-saline soils (Abderrazak et al., 2016). We selected different feature samples on Google high-resolution imagery, adjusted the band combinations of remote sensing imagery most suitable for saline soil extraction, and compared the spectral features of the different samples, using a supervised classification approach to identify saline soil distribution initially. In this process, the slope data, image texture features, and geomorphological difference features of the samples in the study area can be compared to better identify the distribution of saline and alkaline land and the slope range of saline and alkaline land is distributed between 0-0.5, combined with the field sampling points to modify the interpretation flag, continuous interpretation, and verification, to improve the accuracy of remote sensing interpretation.

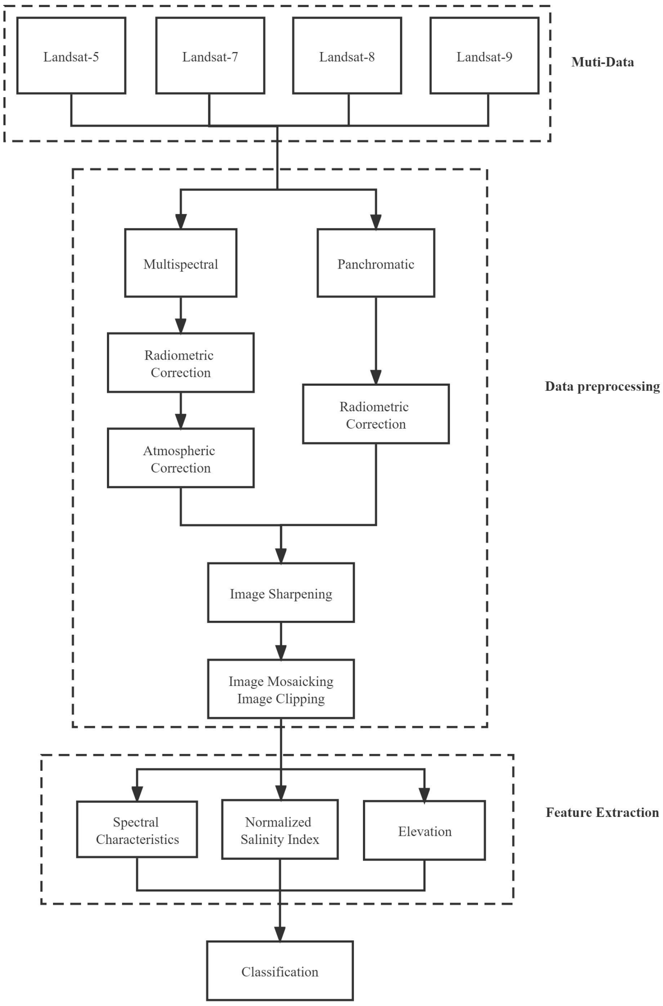

Figure 2. Flow chart of data processing

3. Results

3.1 Spatial distribution of soil salinisation

Remote sensing inversion of salinization in the Shiyang River Basin from 2002 to 2022 was carried out based on the selected samples of mild, moderate, and severe soil salinization (Fig. 3). The results showed that the salinization of the basin gradually increased from upstream to downstream, especially in the downstream of the basin near Qingtu Lake, where the salinization of the soil was the most serious. Salt accumulation areas in the Shiyang River basin are widely distributed in Minqin County, Gulang County, and Liangzhou District of Wuwei City, as well as Jinchuan District and Yongchang County of Jinchang City, among which the most severe salinization is mainly distributed in the eastern part of Minqin County, with the most extensive distribution of moderately saline areas, and the less severe salinization of soils in the middle and northern parts of Gulang County and the northwestern part of Yongchang County.

The overall change in the watershed from 2002 to 2022 shows that the salinized area is on an upward trend. The area most affected by salinization is Minqin County in the northern part of the watershed, including Donghu Township in the east, Nanhu Township in the southwest, and Changning Township in the south, where soils are heavily salinized. However, the salinized area is on a downward trend. Especially in 2007, the salinisation area in Nanhu Township was significantly reduced. In Liangzhou District in the south-central part of the watershed, the degree of soil salinity has mostly stayed the same over the years. Soils in Jinchuan District in the western part of the watershed showed moderate salinisation for a long time, and the salinised area showed a slight decrease during the 21 years. The southeastern part of the watershed has a lesser degree of salinization, with a smaller proportion of heavy salinization, and the area of both degrees of soil has decreased. However, the salinization in Yongchang County in the west-central part of the watershed was gradually severe, and until 2007, only localized areas of soil were subject to mild salinization. However, from 2012 onwards, large areas of soil were salinized, with moderate salinization predominating, and the area of salinized soil increased yearly.

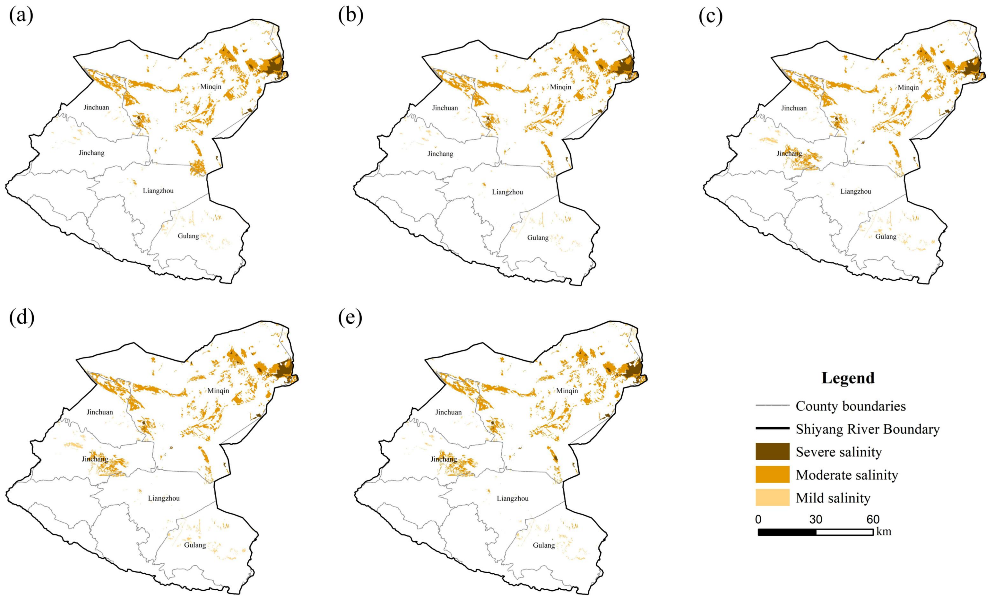

Figure 3. Spatial distribution of salinisation in the Shiyang River Basin (a: 2002; b: 2007; c: 2012; d: 2017; e: 2022)

3.2 Temporal changes in soil salinisation

According to the administrative boundaries, the plot units in the study area were first divided into five parts. Then, the temporal changes of the soil salinization area in the five parts were counted separately from 2002 to 2022. At the same time, the year-by-year trend of mildly saline, moderately saline, and heavily saline soils in the study area was analyzed (Fig. 4).

From 2002 to 2022, the overall salinized area of the basin shows an increasing trend, with an average annual growth rate of 1881.9hm^2/a. In terms of severity, the area of heavy salinization shows an increasing trend since 2002, with a slight decrease in 2007, and then continues to increase, with its area as a proportion of the whole basin area rising from 0.64% to 0.67%, with a growth rate of 262.99hm^2/a. The area of moderate salinization has been at a high level as a proportion of the total watershed area and has been gradually decreasing since 2002-2007. The area has further expanded after 2007, and then there is a slight decrease in 2022, with an annual increase of 934.33hm^2. The area of mild salinization in the watershed has been shrinking since 2002, but from 2007-2012, the area has continued to increase and exceeded 20,000hm^2 reached the maximum value in 2012, and decreased after 2012 with a rate of change of 684.56hm^2/a. From the subregion, the salinized area of Gulang (GL) exceeded 10,000 hm^2 in 2012 and then decreased after 2017, with a rate of change of 470.03 hm^2/a. YC had the most pronounced trend of salinization growth, with a significant increase in its salinized area from 2007, and its share of the salinized area in the Shiyang River Basin reached a maximum of 12.15 %. Compared with the first two regions, the salinized area of the other three regions showed a decreasing trend. Among them, Minqin (MQ) and Jinchang (JC) showed a continuous decrease in salinised area since 2002, and the rate of change of JC was -291.41 hm^2/a. The rate of change of MQ was -5317.1 hm^2/a, and its share of the salinized area was reduced from 83.86% to 74.66%, which shows that the salinized area of MQ was expanded from the general viewpoint, but the Minqin's heavily salinized area is further expanding.LZ's salinized area reached the lowest value in 2007, and from 2007 to 2017, the salinized area further expanded and then slightly decreased, but its share of the salinized area in the whole watershed is small, and the change is not very fluctuating.

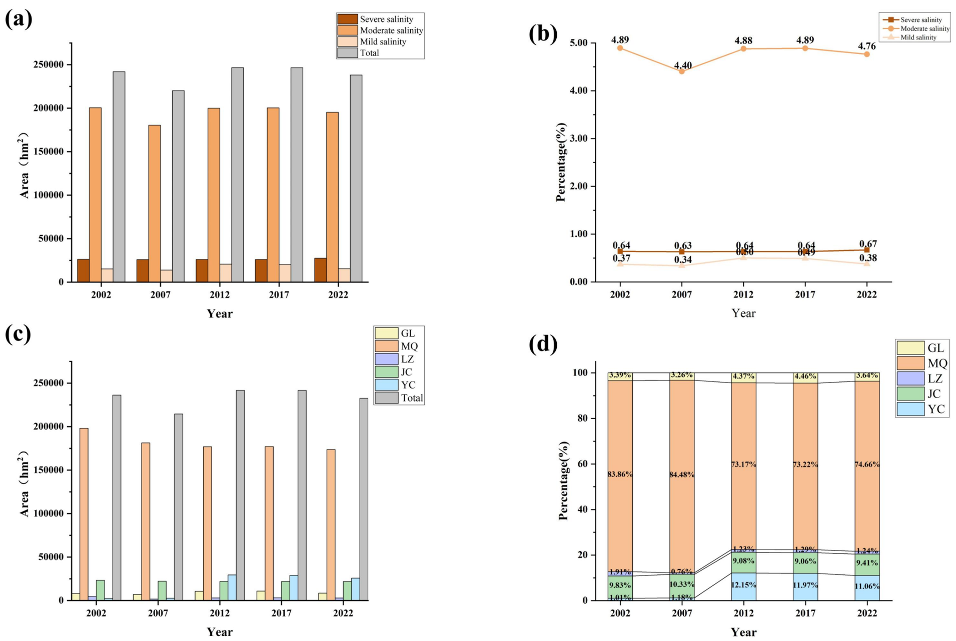

Figure 4. Changes in soil salinisation area in the Shiyang River Basin (a: changes in the three degrees of salinisation and total salinisation area; b: percentage of the three degrees of salinisation;

c: changes in the five counties and total salinisation area; d: percentage of salinisation area in the five counties and districts)

4 Discussion

4.1 Soil salinisation and basin water conservancy project

With the advancement of the water transfer project and the increase of water transfer, the amount of farmland irrigation water is bound to increase substantially, and the input of external water will inevitably break the equilibrium state between regional soil, vegetation, and climate, so it is necessary to pay attention to the salinization problem brought about by farmland irrigation (Thorslund et al., 2021). In the long term, secondary salinisation is a major potential obstacle to the sustainability of inter-basin water transfers. The negative effects are reflected in both the evaporation processes that are altered by the transfer of water for irrigation and the rise in the water table caused by the foreign water. The connectivity between groundwater and soil water increases, and the trend of salt enrichment to the surface through evaporation becomes more obvious. Low rainfall and high evapotranspiration in arid areas will lead to the accumulation of large amounts of salts dissolved in water on the soil surface to form salinization.

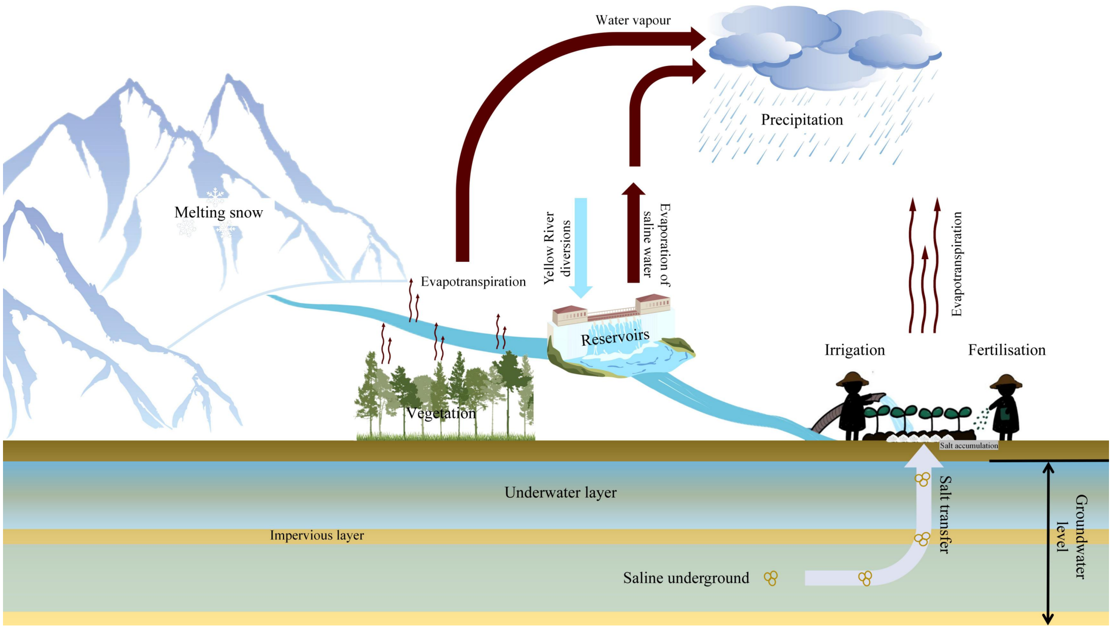

Figure 5. Conceptual diagram of the salinisation cycle in arid zones

In the upper reaches of the Shiyang River Basin, natural water sources such as precipitation and snowmelt water are introduced into the irrigation area; in the middle reaches, the construction of reservoirs and canals is used to improve the supply of water resources in the irrigation area; in the lower reaches, the main source of water is water coming from the upper reaches of the Shiyang River; and a large portion of the water in Hongyashan Reservoir, in addition to the water coming from the upper reaches of the Shiyang River, is derived from Jingdian transmission (i.e., the Yellow River transferring water) and the Hongyashan Reservoir's transferring water to Qintuhu to regulate the pattern of water use for irrigation. The Xiyang River has been transferring water to Minqin since 2006. The Jingdian II water transfer project has transferred water from the Yellow River to the Minqin area for 12 consecutive years since 2011. These projects have considerably eased the pressure on Minqin's water resources. Meanwhile, from the trend of soil salinization area change in the Minqin area in the past 21 years (Fig. 4c and Fig. 4d), the salinized area in the Minqin area is gradually decreasing. In 2012, the salinized area of the Minqin area in the salinized area of Shiyang River Basin showed a sharp decline in the percentage of the area. Then, it has been kept in a stable state related to the basin water transfer. This is because the water transfer project slows down the rate of decline of the groundwater table and improves the surface water utilization rate. When the groundwater level falls, the salts in the soil are usually adsorbed on the soil surface and not easily washed away by the water body, which will cause the accumulation of salts. However, at the same time, too much water transfer or irrational irrigation will also lead to excessive water accumulation on the soil surface, coupled with the intense evaporation in the Minqin area, the evaporation on the soil surface will increase, and the salts will further accumulate on the soil surface. Hence, the proportion of heavy salinity in the Minqin area shows a rising trend. When the surface water use efficiency is low, the irrigation water cannot fully penetrate the deep soil layer but only stays on the soil surface. Then, the salts will stay on the soil surface through evaporation, which will aggravate the degree of soil salinization. Although the water transfer project is designed to improve the ecological and water shortage status of inland river basins in arid areas, it also aggravates salinization in Minqin.

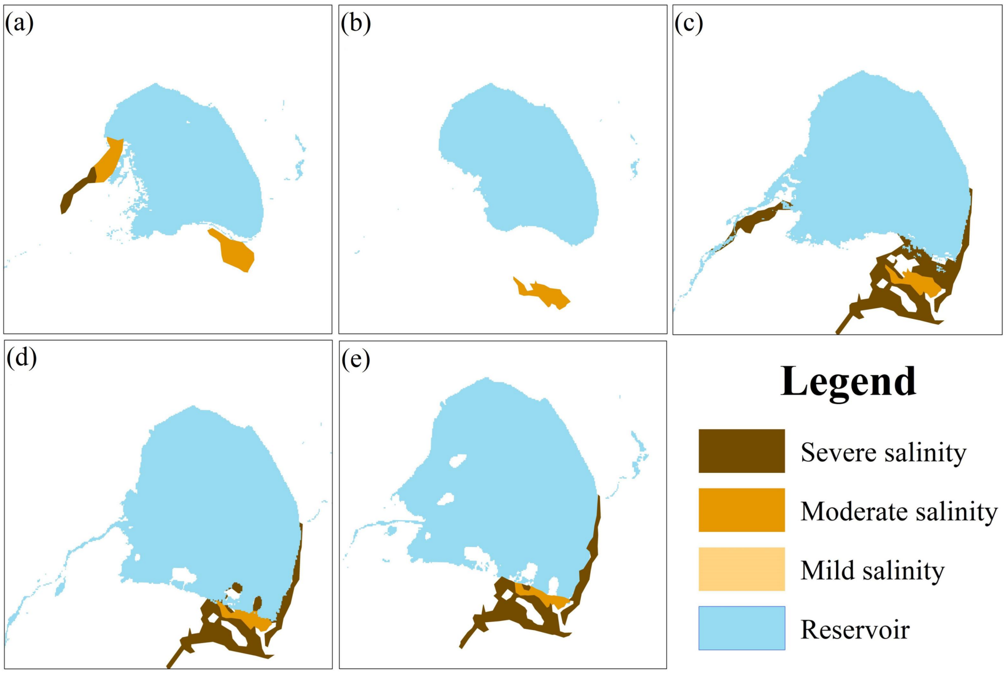

Figure 6. Changes in water body area and salinity in Red Bluff Mountain Reservoir (a:2002; b:2007; c:2012; d:2017; e:2022)

Irrigation around the reservoir is a significant cause of increased soil salinity. The Red Cliff Mountain Reservoir is located in the middle of the desert, and its western side is built on the Red Cliff Mountain, while the other sides are manufactured. The Red Cliff Mountain Reservoir is intended to improve the downstream ecological water shortage, but as the reservoir area increases, the downstream terrestrial water storage is decreasing. The conductivity of groundwater is an essential indicator for assessing its salinity. By measuring the EC value of groundwater in Hongyashan Reservoir from 2017-2019, it was found that the EC value of groundwater in Hongyashan Reservoir remained above 500 μs/cm, beyond the range of low-salinity water. There was a slight upward trend in recent years, with an increase of 14.119 μs/cm from 2017 to 2023.

From 2002 to 2022, as the area of Hongyashan Reservoir expanded, the salinization of the soil around it gradually increased (Fig. 6). In 2002, the area of the reservoir was relatively small, and the soil along the foot of Hongyashan Mountain at the west was heavily and moderately salinized. Part of moderately salinized land also appeared in the southeast. In 2007, water storage in the western part of the reservoir increased. The salinized area in the southeast shifted southward (Fig. 7). In 2012, soil salinization in the southern part of the reservoir increased dramatically to heavy salinity and, in the south-western corner near the Shiyang River area, heavy salinization also occurred. From 2012 to 2022, with the raising and expansion of the reservoir, the soil salinization has remained the same, and the salinization area around the reservoir has further expanded. Moreover, the reservoir's water level is raised, coupled with an arid climate and low rainfall, which will intensify soil surface water's evaporation, leading to the accumulation of salts in the surface soil and a gradual increase in the degree of soil salinization.

4.2 Soil salinisation and irrigation

The development of irrigated agriculture is necessary to meet the growing food needs of the global population (Jägermeyr et al., 2017). At the same time, the risk of salinization of agricultural land, grassland, and wasteland is exceptionally high. Salinization and irrigation are two common but often neglected issues in agricultural production. It is essential to clarify the relationship between salinization and irrigation and provide possible solutions. There are 27 irrigation districts in the Shiyang River Basin (Fig. 7), the largest of which is the Hongyashan Irrigation District, with an area of 161,945.17 hm2. Among the irrigation districts with more serious soil salinization are the Hongyashan Irrigation District, the Changning Irrigation District, the Dongdaha Irrigation District, the Nanhu Irrigation District, the Donghe Irrigation District, the Xiyinghe Irrigation District, and the Qinghe Irrigation District, with most of them having a medium degree of salinization. A small portion of them were mildly salinised, among which the Dongdaha Irrigation District was moderate from 2007 to 2012. Irrigation District in 2007-2012, soil salinisation was more serious, and the salinised area increased substantially. In the Gulang River Irrigation District, Wujiajing Irrigation District, Huangyang River Irrigation District, Huangyan Irrigation District, Qiduntai Irrigation District, Jingdian Irrigation District, Dajing River Irrigation District, Qingyuanjing Irrigation District, Zaomu River Irrigation District, Jinta River Irrigation District, Jinyangjingyuan Irrigation District, Yongchang Irrigation District, Xiehe Irrigation District, Siba Irrigation District, and Jincheon

Irrigation District, the degree of soil salinization was mild. The area of salinisation was relatively small. Regarding spatial distribution, irrigation areas with severe salinization are in the middle and lower reaches of the watershed, and those with lesser or no salinization are in the upper regions. This is closely related to evaporation in arid regions, a vital salinization driver. The evapotranspiration in the Shiyang River basin has apparent vertical and regional zonation. The upstream is located in the alpine semi-arid humid zone of the Qilian Mountains, with an altitude of 2000-5000 m. The annual evaporation is 700-1200 mm, the annual evaporation in the middle reaches 1300-2000 mm, and in the downstream, it is as high as 2000-2600 mm. Evaporation gradually increases from the upstream to the downstream, and salinization is gradually aggravated. Among them, the area of soil salinization in Gulang River and Wujiajing irrigation areas increased continuously from 2002 to 2017, while the area decreased from 2017 to 2022, and the area of soil salinization within other irrigation areas did not change much.

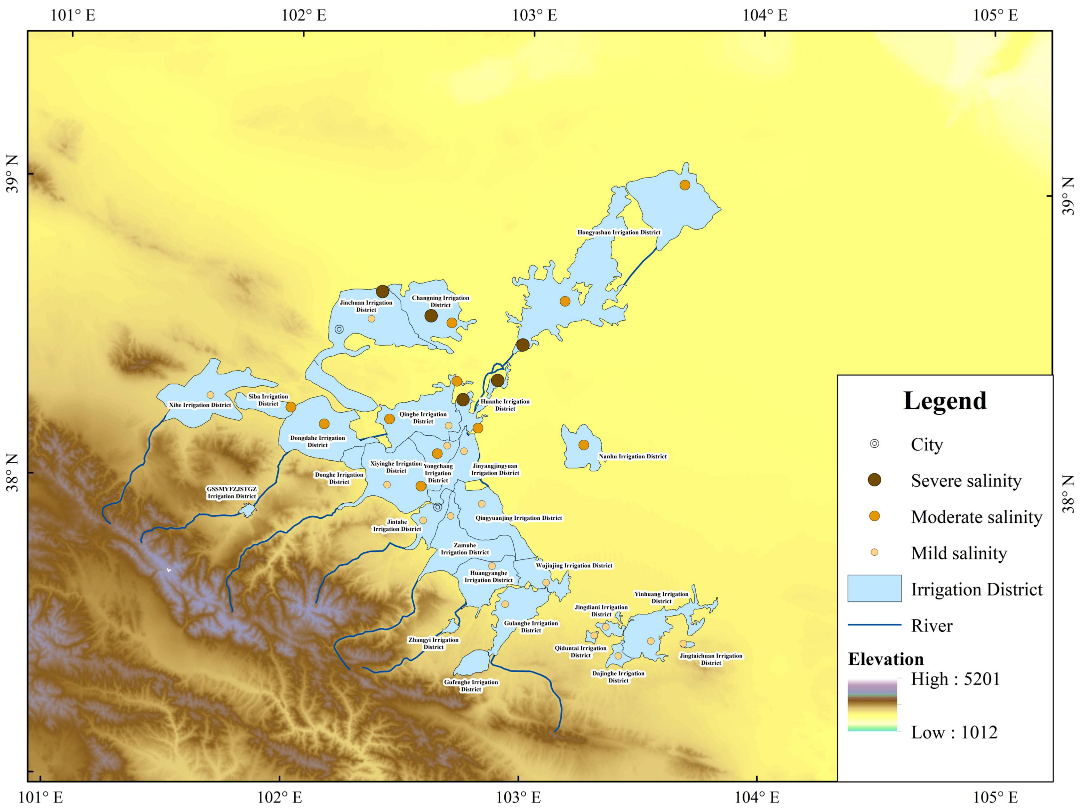

Figure 7. Distribution of irrigation areas in the Shiyang River Basin

Most soil salinization in the Shiyang River Basin is found in irrigated areas. In irrigated areas, problems such as long-term over-irrigation and poor drainage often occur, accumulating salts and alkaline substances in the soil, thus causing soil salinization. In addition, the monoculture of land within irrigated areas, where only one or a few crops are often grown, also tends to lead to excessive accumulation of certain elements in the soil, thus aggravating soil salinization. For example, in the watershed's middle reaches, crops' cropping pattern is adjusted with changes in topography, climate, and land use patterns. In the lower reaches, the cropping pattern is more homogeneous than in the middle reaches, with cotton, wheat, and maize as the main crops, which will affect soil salinization to a certain extent. The relationship between salinity and irrigation is apparent: over-irrigation increases the concentration of salts in the soil, leading to salinity problems. In addition, soils with a high salt content affect irrigation water quality, affecting plant growth and yields.

5 Conclusion

This study used high-resolution remote sensing data to quantify the changes in soil salinity and its impact on the water cycle mechanism in an inland river basin in the arid zone from 2002 to 2022. The salinized area of the basin showed an increasing trend with an interannual growth rate of 1881.9 hm2/a, and the degree of salinity gradually increased from southwest to northeast. The area of heavily, moderately, and lightly salinized soil all showed an increasing trend, with annual growth rates of 262.99hm2, 934.33hm2, and 684.56hm2, respectively. Farmland, grassland, and wasteland are at the most significant risk of being converted into saline soils, challenging farmland management. From the present point of view, external water transfer plays a positive role in the water cycle of the basin, improves the water scarcity of the basin, and slows down the trend of rapid development of soil salinization. However, its impact on the future water resources is subject to further debate. Although the reservoir provides help for ecological water transfer in the lower part of the basin, soil salinization has already occurred in its vicinity, which harms the soil environment of the farmland. Water transfer projects and river water are the primary sources of irrigation water for farmland in the basin, and the distribution of saline soils is mainly within the irrigation area, which means that rational land management and irrigation techniques are essential to mitigate the salinization problem. Moreover, the salinization problem must be simultaneously grasped in water bodies and soils. Human activities have seriously altered the soil quality of the basin and further affected the water cycle and water resource conditions. This study will provide a more scientific basis for basin agricultural and water resource management.

Conflict of Interest Statement

The authors declare no conflicts of interest.

Author contributions statement

Gaojia Meng and Guofeng Zhu conceived the idea of the study; Yinying Jiao, Dongdong Qiu and Yuhao Wang analyzed the data; Rui Li, Longhu Chen and Qinqin Wang participated in the drawing; Gaojia Meng wrote the paper; Siyu Lu, Enwei Huang, Jiawei Liu and Wentong Li checked and edited language. All authors discussed the results and revised the manuscript.

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Data Availability Statement

The 30m land use classification data for the Shiyang River Basin used in this study are available in the public domain (https://doi.org/10.5281/zenodo.4417810); Landsat series data were obtained from Earth Explorer service (https://earthxplorer. usgs.gov).

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