Subject 1: Water Utilization

Composition and classification of salts in surface water and groundwater in a semi-arid irrigated area - Case study in Mirzaabad district, Uzbekistan -

Keisuke OMORI[1], Yulia I. SHIROKOVA[2] and Junya ONISHI[1]

Summary

The Mirzaabad district in the Syrdarya Region of Uzbekistan has a secondary soil salinization problem due to excessive irrigation and increased salt contents in shallow groundwater. This district is separated into the Old and New zones according to history and circumstances of irrigation development. The Old zone is located near the Syr Darya River, has abundant water and has been irrigated for centuries. In contrast, the New zone, located in the Golodnaya steppe, was developed into irrigated farmland through the use of concrete canals and subsurface drainages, and is prone to water shortages. The main drainage canal (main collector) is located near the boundary of these zones.

In this study, we estimated the salt compositions of surface water (irrigation and drainage water) and groundwater in this district, and characterized the different types of mineral species using the chemical equilibrium model Visual MINTEQ. The groundwater composition differed between the two zones, with calcium and magnesium salts dominating the Old zone, and sodium salts dominating the New zone. This difference may result from highly-soluble sodium salts being discharged from the Old zone through the open channel drainages; whereas sediment continues to accumulate in subsurface drainages in the New zone, reducing drainability and discharge of sodium salts, causing them to infiltrate into the shallow groundwater.

Keywords

Dry land, Salt minerals, Surface and groundwater quality, Syr Darya River, Visual MINTEQ

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[1] Japan International Research Center for Agricultural Sciences (JIRCAS)

[2] Scientific Research Institute of Irrigation and Water Problems of the Republic of Uzbekistan (RIIWP)

1. Introduction

Irrigation plays an important role in the agricultural production of Central Asia, and in most areas, crops must be irrigated because of the region's arid climate. Some areas have been irrigated for centuries; however, Soviet central planning also created many irrigation and drainage schemes during the period 1950–1980. At that time, massive plans were implemented for irrigating desert or steppe areas and hundreds of thousands of people moved to there to find work in agriculture. From 1970 to 1989 (the end of the Soviet period), the irrigated areas expanded by factors of 150 and 130 % in the Amu Darya and Syr Darya basins, respectively (World Bank, 2003). In Uzbekistan, intensive development of the newly irrigated areas in the 1960s–1980s caused land degradation due to salinization and waterlogging. Salinization and waterlogging already affect 50 % of the irrigated areas. In 1994, irrigation covered 4.20 million ha in Uzbekistan, and of this 2.14 million ha has been salinized by irrigation (FAO, 2013).

The causes of soil salinity in Uzbekistan are (a) cultivation of naturally-saline lands, (b) a rise in secondary salinization because of the influx of mineralized (saline) groundwater from the higher plateaus with intensive irrigation and (c) increases in the salt content of irrigation water due to disposal of drainage water into irrigation canals (Shirokova et al., 2000). Secondary soil salinization is especially acute in irrigated lowlands, such as the Syrdarya Region, located in the east central and narrowest part of Uzbekistan on the left bank of the Syr Darya River. Virtually all irrigated areas in the Syrdarya Region are saline; 99.1 % of them were assessed as slightly-to-moderately saline in 1999 (MAWR, 2003). This is particularly true of Mirzaabad, one district of the Syrdarya region, which had the highest percentage of irrigated land within the moderate-to-severely saline (57.6 %) category (ADB et al., 2008).

Among the major sources of secondary soil salinization are salinity of applied irrigation water as well as depth and salinity of groundwater. Salts from surface waters are deposited directly from the water source and accumulate in the soil profile (Ghassemi et al., 1995); and salinization from groundwater occurs when salts within groundwater reach the soil surface by capillary action (Hillel, 2000).

The degree of secondary soil salinization is more severe in Mirzaabad than in other districts of the Syrdarya region (JIRCAS, 2014), but few studies that included measurement and evaluation of irrigation water and groundwater quality have been published. MAWR (2003) evaluated soil salinization using survey results of salt concentration of irrigation water and soil, and also created a salinity map with cooperation of FAO in the district; however, despite being one of the main causes of salinization, groundwater quality was not well studied.

Therefore, the objectives of this study were to understand the qualities of surface water (irrigation and drainage water) and groundwater in the Mirzaabad district in order to estimate the composition of the solutions and the types of mineral species, and to classify the salt types in the district using the chemical equilibrium model, Visual MINTEQ. We also suggested measures that could be taken in the future so that these analysis results could be useful in drainage improvement and soil management projects in the area.

2. Materials and Methods

2.1 Study area

2.1.1 Geographical and topographical condition

Mirzaabad district (40°19′–40°37′N, 68°26′–68°48′E) is located in the center of the Syrdarya region (**Fig. 1**). According to the statistical data of the Hydro-Geological Melioration Expedition (HGME) of the Syrdarya region in 2010, about 41,772 ha of a total area of 44,000 ha can be irrigated. The district, bordered by the South Kazakhstan region of Kazakhstan, has an extremely arid continental climate with the Syr Darya River forming its eastern border. The source of irrigation water to Mirzaabad is the Syr Darya River. Irrigation water is provided by the Farkhad hydropower station, near the Tajikistan border in the southeast of the Syrdarya region, and the main canals branch toward the west and northwest. The ground slope is gradual with an average gradient of 0.04° toward the northwest.

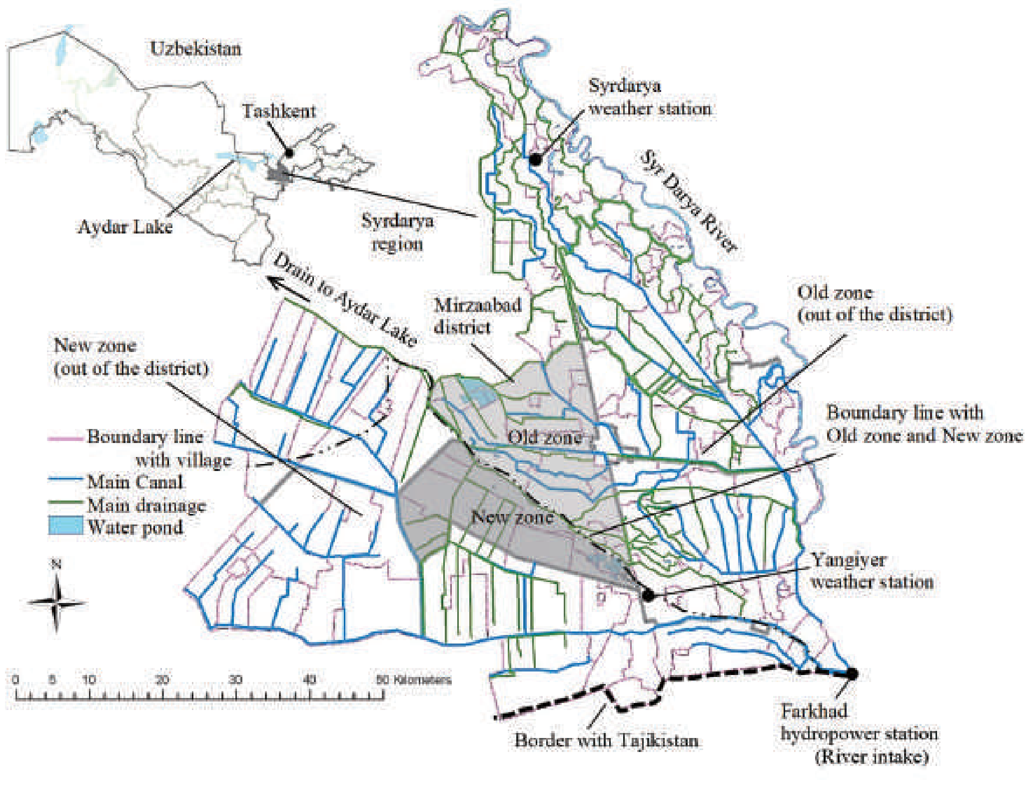

Fig. 1 Survey site and irrigation - drainage network in Syrdarya Region

2.1.2 Climate and soils

Weather observations over a 10-year period (2004–2013) (Syrdarya and Yangiyer weather station data) showed an annual average temperature of 15.5 °C, with the lowest temperature of −23.2 °C in January 2008 and the highest of 44.0 °C in June 2005. Thus, there were large fluctuations in temperature. Annual rainfall was 344 mm on average, and 87 % of this fell during October–April. Evaporation increases as early as April, reaching a maximum in July.

In Mirzaabad, solonchak soils are distributed throughout most of the district, and some calcisols are present on the eastern side (MAWR, 2003). Based on their characteristics, the accumulated salts are presumed to be Na salts, calcium sulfate and calcium carbonate, in order of decreasing water solubility.

2.1.3 Irrigation and drainage facilities

The district is separated into the old irrigation zone (Old zone) in the northeast and the new irrigation zone (New zone) in the southwest according to the history and circumstances of irrigation development. In the Old zone, small-scale irrigation farming was performed using the Syr Darya River from ancient times, and the former Soviet Union started the irrigation development of the Syr Darya River from 1914 (earth canal). The Old zone is close to the Syr Darya River and there is abundant water. In the New zone, modern irrigation techniques (concrete canal) were developed in the prairie area, called Golodnaya steppe, from 1950. The New zone is in the steppe and water shortages are common (JIRCAS, 2010). According to the Department of Pump Station, Energy and Communications in the Syrdarya Region, groundwater is pumped and blended with irrigation water in the area of water shortages during the summer irrigation season.

Drainage networks are used to remove excess surface and groundwater in the district. The types of drainage differ between the Old and New zones. In the Old zone, open channel drainages were constructed (depths of 3–4 m), and drainage water mainly flows in a northwest direction. In the New zone, subsurface drainages were constructed with depths of 2.5–3.0 m. Outlets of the subsurface drainage connect with the open channel drainages in the New zone, but some subsurface drainages have low drainability, because of clogging of pipes with sediment (Okuda and Onishi, 2012). The open channel drainages in the New zone connect with the main drainage canal (main collector). The main collector was constructed in 1965, has a depth of 6–7 m, is located in the center of the district and flows to the northwest. The salts removed from soils by leaching process flow into the Aydar Lake (40°55′N, 66°48′E), the salt lake located in the west of the Syrdarya Region.

2.1.4 Groundwater observations

The HGME of the Syrdarya Region, an effort to better manage the secondary soil salinization problem, was initiated by digging observation wells across the region at a density of one well for every 150 ha to monitor the groundwater table. According to the HGME in 2012, there were 393 observation wells in the Mirzaabad that were 5 cm in inner diameter, 4 m in depth and contained multiple small holes 2–3 m from the ground surface. The HGME observations of the groundwater table during 2010–2012 showed that the groundwater table tended to rise during November–March, and in some periods reached approximately 50 cm from the ground surface. During June–September, rainfall is minor and the amount of evapotranspiration is large and so the groundwater table fell, despite the irrigation period.

2.1.5 Farming situation

Upland cotton (*Gossypium hirsutum* L.), winter wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) are the dominant crops in the district. The peak irrigation period for cotton and rice is June–August, whereas irrigation of winter wheat begins in November. Crops are irrigated with surface furrow and flood methods. Copious leaching is practiced throughout the region, mainly in December, to counteract the high soil salinity. Fields with slightly saline soils receive 2,500 m^3 ha^{-1} of water, and highly saline areas receive up to 4,500 m^3 ha^{-1} (HGME in the Syrdarya Region, 2007).

2.2 Collection and analysis of water samples

The irrigation–drainage network and water sampling points in Mirzaabad are shown in **Fig. 2**. Water samples were collected from the irrigation canals (nine points, including Dustlik canal with three points) and the HGME observation wells (27 points). Two samples were collected from each sampling point. Additionally, samples were also taken from the Farkhad hydropower station (40°13.613′N, 69°09.393′E), Dustlik canal (outside of the district; 40°27.861′N, 69°03.304′E) and drainage canals (19 points). For collecting groundwater samples, bailer samplers (contents 70 mL) were inserted into the HGME observation wells, where water was collected and immediately measured for pH and electrical conductivity (EC). After being filtered through a 0.45-μm filter, the sample was placed in a 100-mL container with a lid and stored in a cool box during the water sampling period. The water was sampled during the four days of 15–18 July 2013.

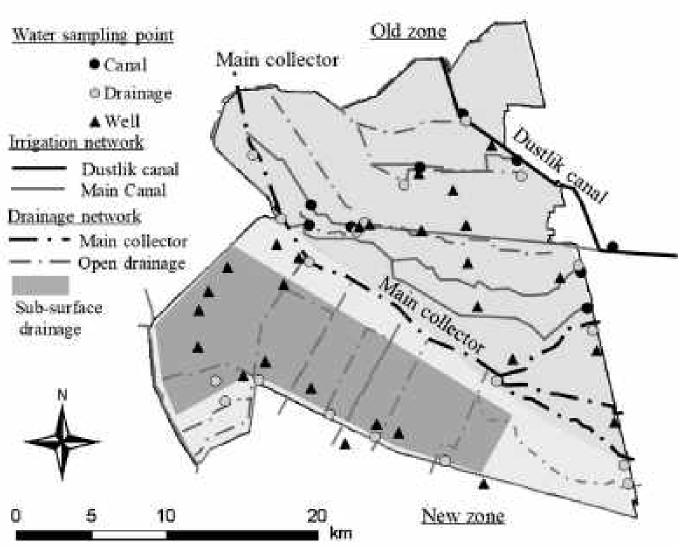

Fig. 2 Irrigation – drainage network and water sampling points in the Mirzaabad district

Collected samples were analyzed in a laboratory. Samples were appropriately diluted, and Ca^{2+}, Mg^{2+}, Na^+ and K^+ were measured with ICP atomic emission spectroscopy. Cl^-, SO_4^{2-} and NO_3^- were measured using ion chromatography; and HCO_3^- by acid-base titration (pH 4.8 alkalinity) using 0.05 mol L^{-1} sulfuric acid.

We calculated the sodium adsorption ratio (SAR) using Eq. (1), where, Ca^{2+}, Mg^{2+}, and Na^+ concentrations are expressed in units of $mmol_c$ L^{-1}. SAR is an indicator of sodicity hazard.

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \quad (1)$$

To evaluate the potential chemical reactions in irrigation water and groundwater, the solution concentration and the saturation index (SI) of the water were calculated using chemical equilibrium model Visual MINTEQ version 3.00 (Gustafsson, 2012). The model has an extensive thermodynamic database that allows for the study of ion speciation, solubility and equilibrium of solid and dissolved phases of minerals in an aqueous solution (Gustafsson, 2012). This program is the Windows version of MINTEQ that was originally developed by the US EPA (Allison et al., 1991). Nagaraju et al. (2014) used Visual MINTEQ, based on water analysis results, to predict the mineral species in groundwater to assess its quality for irrigation purposes.

The SI is calculated by comparing the chemical activities of the dissolved ions of the mineral (ion activity product, IAP) with their solubility product (K_{sp}). SI is calculated using Eq. (2).

$$SI = \log\left(\frac{IAP}{K_{sp}}\right) \tag{2}$$

The SI quantitatively indicates the dissolution and precipitation reactions in surface water and groundwater. Negative, zero and positive values of SI, respectively, indicate under-saturation, equilibrium and over-saturation of water with respect to dissolved minerals.

The measured Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-} and HCO_3^{-} concentrations (mmol L^{-1}) were entered into the Visual MINTEQ program. The pH range was 7–10 using the sweep option which is for the validation of the behavior of pH and carbonate ion varieties in the software. The equilibrium amounts of the selected solutions (10 types: calcium carbonate, calcium bicarbonate, calcium sulfate, calcium chloride, magnesium carbonate, magnesium sulfate, magnesium chloride, sodium bicarbonate, sodium sulfate and sodium chloride) were obtained using the pH range, and the mineral species with high SI (i.e. SI > 0, precipitation; or SI ≈ 0, saturated) were determined.

3. Results

3.1 Water quality in the study area

Table 1 shows the water quality characteristics of the different water sources: irrigation water, drainage water and groundwater. Groundwater was divided into the Old and New zones. The boundary between the two zones was roughly divided into north and south of the main collector.

Table 1 Chemical properties of irrigation water, drainage water and groundwater

	(mmol$_c$ L^{-1})				
	Irrigation water		Drainage	Groundwater	
	Water sources	Canal water	water	Old zone	New zone
Ca^{2+}	5.95±0.06	6.30±0.72	14.54±5.57	17.03±10.28	23.18±8.62
Mg^{2+}	5.01±0.12	5.36±0.63	16.34±15.22	21.34±17.62	61.94±68.57
K^{+}	0.29±0.00	0.32±0.04	0.51±0.35	1.18±0.71	1.64±1.59
Na^{+}	3.95±0.05	4.29±0.61	26.57±43.94	26.30±25.46	197.54±283.55
Cl^{-}	2.09±0.01	2.42±0.40	18.35±36.06	15.70±12.23	135.50±243.16
SO_4^{2-}	10.81±0.24	11.62±1.39	37.56±32.11	47.41±38.27	157.70±168.07
NO_3^{-}	0.03±0.00	0.03±0.00	0.03±0.02	0.02±0.03	0.13±0.15
HCO_3^{-}	2.15±0.12	2.07±0.32	2.55±1.18	3.06±3.01	1.47±1.51
EC (dS m^{-1})	1.46±0.02	1.48±0.05	4.52±4.43	5.00±2.81	17.60±19.82
pH	8.23±0.05	8.38±0.11	8.19±0.26	8.15±0.41	7.99±0.47
SAR	1.69±0.01	1.77±0.15	5.52±5.72	7.05±6.33	23.52±26.37

Note: mean value ± S.D.

3.1.1 Irrigation water

The EC of irrigation water (including the water source) was 1.40–1.56 dS m^{-1} (average 1.46 dS m^{-1}) and pH was weakly alkaline at 8.1–8.5. According to the diagram of Richards (1954) for the classification of irrigation water using EC and SAR, the water quality was classified as C_3-S_1 (High-salinity water, Low-sodium water). Irrigation water is provided by the Farkhad hydropower station (**Fig. 1**) and is distributed to irrigation canals through the district, and so irrigation water quality did not differ between the Old and New zones.

3.1.2 Drainage water and groundwater

There were significant differences in salt concentrations among the drainage water samples, and the maximum concentration for total cations was 17.5 times the minimum value measured. The highest salt concentration in drainage water was for the sampling point at the end of the main collector: EC was 22.1 dS m^{-1} and Na^+ concentration reached 207.9 $mmol_c$ L^{-1}. When this sampling point was excluded from the data set, the range of EC for drainage water was 1.4–7.3 dS m^{-1}. Although there were differences in salt concentrations, the ion composition was nearly the same at every sampling point. The average ion percentages for drainage water at 18 sampling points were Ca^{2+} (33.6 %), Mg^{2+} (30.2 %), and Na^+ (35.1 %) for cations; and Cl^- (20.7 %), SO_4^{2-} (71.4 %) and HCO_3^- (7.9 %) for anions.

In groundwater, there were also significant differences in salt concentrations among samples. Salt concentration in groundwater tended to be higher in the New than the Old zone. Notably, the mean Na^+, Cl^- and SO_4^{2-} concentrations in the New zone were 197.5, 135.5 and 157.7 $mmol_c$ L^{-1}, respectively, which were 7.5, 8.6 and 3.3 times the values for the Old zone.

The relationship between EC and the sum of the cation concentrations of drainage water and groundwater was determined and a clear linear relationship was obtained, as shown in Eq. (3).

$$\textit{Total cations}\ (\text{mmol}_c\ \text{L}^{-1}) = 13.726 \times EC\ (R^2 = 0.9846) \quad (3)$$

The Na^+ concentrations for drainage water and groundwater at the sampling points are shown in **Fig. 3**. The highest salt concentration and Na^+ concentration occurred for the sampling point at the end of the main collector, likely because salts discharged through the district's drainage network accumulated there.

There were three points in the New zone with extremely high Na^+ concentrations: 490.6, 777.7 and 861.2 $mmol_c$ L^{-1}. There was no cultivation or irrigation at these points and weeds were flourishing. Furthermore, groundwater samples were categorized according to ion composition into the following groups: (a) sites where the ratio of Na^+ to the whole cation concentration was higher than for Ca^{2+} or Mg^{2+} (11 points; **Fig. 3**), (b) sites where both Ca^{2+} and Mg^{2+} were more abundant than Na^+ (seven points; **Fig. 3**) and (c) sites where Ca^{2+}, Mg^{2+} and Na^+ were present in approximately the same ratio (nine points; **Fig. 3**). At the 11 points categorized as (a) above, SAR was 9.28–80.02, showing continuously high values. Areas of very high Na^+ water (SAR > 26) are unsuitable for irrigation purposes (Richards, 1954).

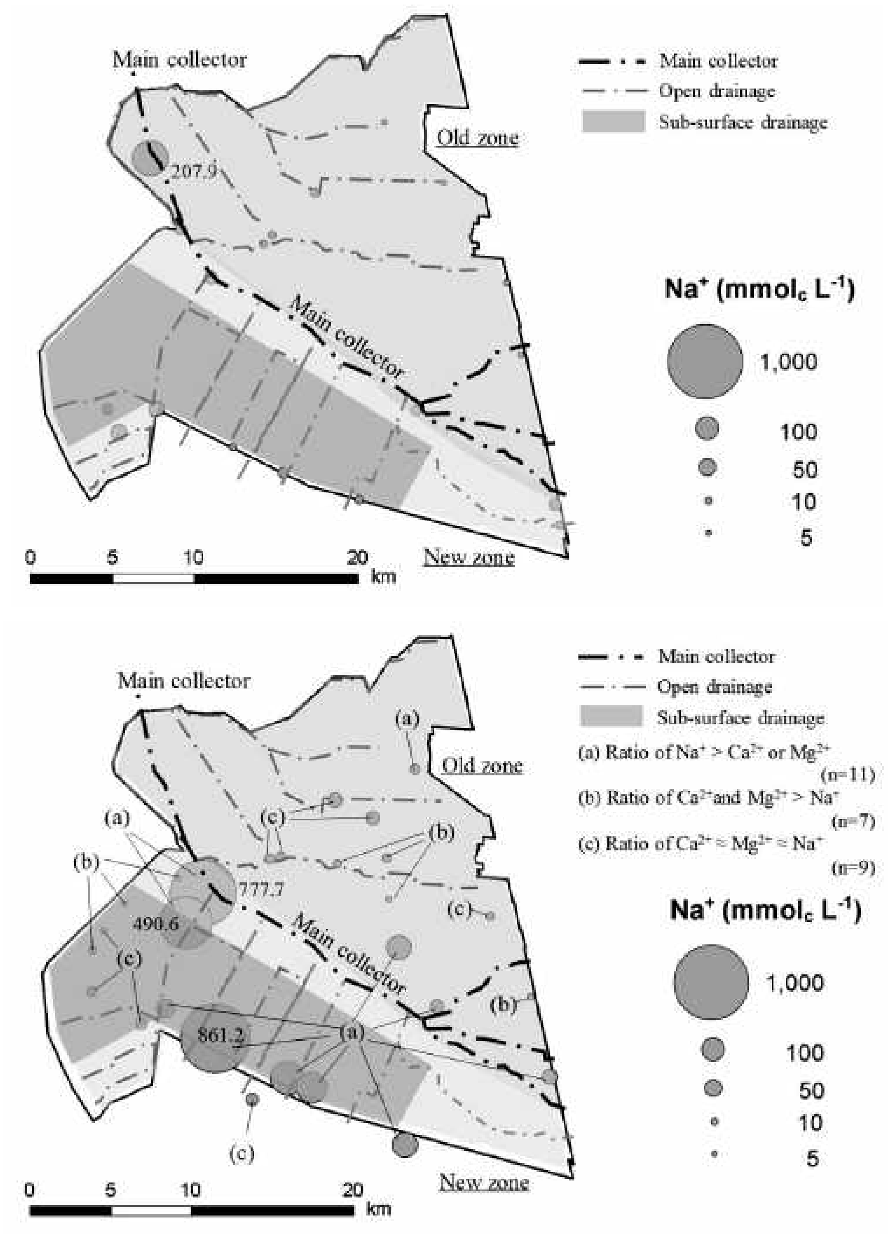

Fig. 3 Distribution of Na^+ concentration for drainage water (upper) and groundwater (lower) at the sampling points

3.2 Estimation of solution composition and types of mineral species

Using the concentrations of cations and anions in irrigation water and groundwater in Mirzaabad (**Table 1**), the types of mineral species were estimated using the chemical equilibrium model, Visual MINTEQ. This showed that the irrigation water contained calcium carbonate (2.8 %, molar concentration ratio of total concentration, mean value for nine sampling points), calcium sulfate (51.3 %), sodium sulfate (4.0 %) and magnesium sulfate (36.7 %) in decreasing order of solubility. In addition, the mineral species were dolomite ($CaMg(CO_3)_2$, SI = 1.79 ± 0.27), calcite ($CaCO_3$, SI = 0.85 ± 0.13), magnesite ($MgCO_3$, SI = −0.21 ± 0.14) and gypsum ($CaSO_4 \cdot 2H_2O$, SI = −0.88 ± 0.06) in descending order of SI.

The compositions of solutions in groundwater were classified into four types according to molar concentration ratios in the total concentration: (a) Ca-type, where Ca salts accounted for 50 % or more; (b) Mg-type, where Mg salts accounted for 50 % or more; (c) Ca+Mg-type, where Ca and Mg salts were in equilibrium; and (d) Na-type, where Na salts accounted for 50 % or more. **Table 2** summarizes the composition of main solutions and estimated mineral species in groundwater for each of the four types. For the Ca-, Mg- and Ca+Mg-types, the composition of solutions in groundwater were calcium sulfate and magnesium sulfate in decreasing order of solubility, and mineral species were carbonates and sulfates of Ca and Mg, such as dolomite (SI = 1.62 ± 0.53), calcite (SI = 0.92 ± 0.21), aragonite ($CaCO_3$, SI = 0.78 ± 0.21), vaterite ($CaCO_3$, SI = 0.36 ± 0.21), magnesite (SI = 0.10 ± 0.34), gypsum (SI = −0.23 ± 0.26) and anhydrite ($CaSO_4$, SI = −0.58 ± 0.34). Mirabilite ($Na_2SO_4 \cdot 10H_2O$) was also deposited in the Mg- and Ca+Mg-types.

Table 2 Main solutions and estimated mineral species in groundwater calculated by Visual MINTEQ

Type	Main solutions	Concentrations (mmol L^{-1})	Ratio (%)	Mineral species	Number of sampling points
Ca	$CaSO_4$	0.8–4.9	39.3–70.1	Dolomite, Calcite,	7
	$CaCO_3$	0.0–0.4	0.1–20.0	Aragonite, Vaterite,	
	$CaCl_2$	0.0–0.1	0.4–1.1	Gypsum, Anhydrite	
Mg	$MgSO_4$	0.2–16.5	43.9–54.9	Dolomite, Magnesite,	5
	$MgCO_3$	0.0–0.3	0.0–33.6	Anhydrite, Mirabilite	
	$MgCl_2$	0.1–1.0	1.1–11.0		
	Na_2SO_4	0.1–8.2	8.9–28.5		
Ca + Mg	$CaSO_4$	2.9–5.5	33.3–51.4	Dolomite, Calcite,	9
	$MgSO_4$	2.7–5.2	37.1–45.7	Magnesite, Vaterite,	
	$MgCl_2$	0.1–0.2	0.8–2.9	Gypsum, Anhydrite,	
	Na_2SO_4	0.2–3.6	2.8–26.3	Mirabilite	
Na	Na_2SO_4	0.1–135.2	21.9–41.3	Mirabilite, Halite,	6
	NaCl	0.4–34.6	6.7–54.6	Gypsum, Dolomite,	
				Anhydrite	

The Na-type groundwater solutions included sodium sulfate and sodium chloride in order of decreasing solubility, and the mineral species were sulfates and chlorides of Na, such as mirabilite (SI = 0.95 ± 0.91) and halite (NaCl, SI = 0.22 ± 0.60). Gypsum, dolomite and anhydrite were also deposited.

The distribution of Ca-, Mg-, Ca+Mg- and Na-types in groundwater is shown in **Fig. 4**. The Na-type was distributed around the main collector in the New zone; and Ca-, Mg- and Ca+Mg-types were distributed in parts of the Old and New zones. The Na-type was mainly distributed in the subsurface drainage facilities, and was generally consistent with areas that had high Na^+ concentration in groundwater (**Fig. 3**).

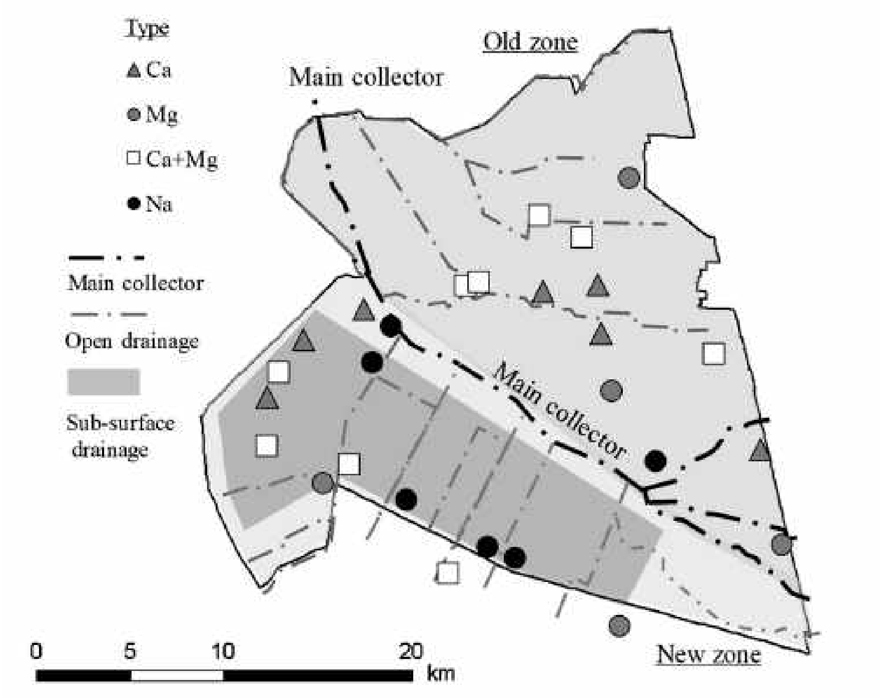

Fig. 4 Distribution of the four type salts (Ca, Mg, Ca+Mg and Na) in groundwater.

The four types of groundwater solutions classified according to the Visual MINTEQ calculation using the Piper (1944, 1953) diagram that expresses the ionic characteristics of groundwater quality, and classifications for irrigation water, are shown in **Fig. 5**.

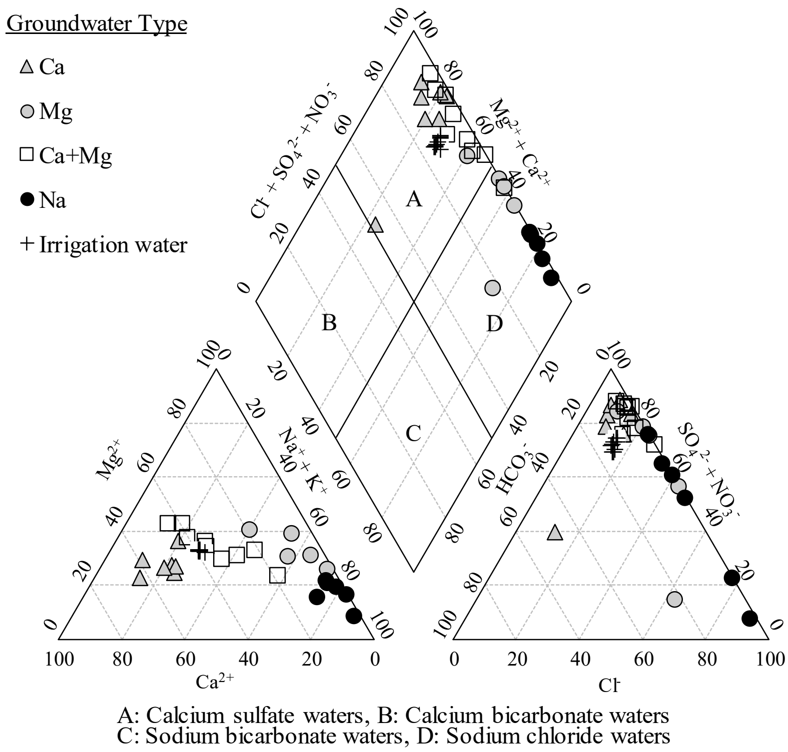

Fig. 5 Piper diagram of groundwater and irrigation water.

In groundwater, Ca-, Mg-, Ca+Mg- and Na-types were compatible with the cations of the ternary diagram (lower left side; **Fig. 5**), but 80 % of Mg-type and 11 % of Ca+Mg-type were categorized within the Na-type cation plots in the ternary diagram (**Fig. 5**). For this reason, mirabilite was also included in these types when using the Visual MINTEQ calculation.

Irrigation water was classified as calcium sulfate waters (upper side of the diamond diagram; **Fig. 5**).

4. Discussion

In Mirzaabad, calcium sulfate and magnesium sulfate accounted for the majority of the salt solutions in irrigation water, and the mineral species mainly comprised dolomite (SI = 1.79 ± 0.27) based on the Visual MINTEQ calculations. There was no difference in irrigation water quality between the Old and New zones. However, groundwater in the Old zone contained large amounts of Ca and Mg salts, such as dolomite (SI = 1.62 ± 0.53) and calcite (SI = 0.92 ± 0.21), and the ion composition of the irrigation water was in conformity with the Piper Diagram, indicating that the groundwater in the Old zone likely results from the permeation of irrigation water (**Fig. 5**).

In terms of the drainage water, the highest salt concentration was at the end of the main collector, likely due to accumulation of the salts discharged by the district drainage network. The ion composition was almost identical throughout the rest of the main collector, with no difference in drainage water quality between the two zones.

In this study, groundwater was collected at 27 points from observation wells. The salt concentration and ion composition of the groundwater was clarified, based on the analysis, and classified into Ca-, Mg-, Ca+Mg- and Na-types. Groundwater in the New zone contained a high concentration of Na salts, and the mineral species mainly comprised mirabilite (SI = 0.95 ± 0.91) and halite (SI = 0.22 ± 0.60) (**Table 2**). Sites with Na-type groundwater composition were plotted on the Piper diagram and classified as sodium chloride waters (**Fig. 5**). The difference between the composition of groundwater in the Old and New zones could be attributed to differences in site conditions and the circumstances surrounding the development of irrigation. The Old zone is located near the Syr Darya River, and so has abundant water and has been irrigated since ancient times. Open drainages are maintained in this zone, and it is thought that highly-soluble salts such as Na salts are collected with water through the open channel drainages and discharged from this zone. In contrast, the New zone is located in the lowest part of the Golodnaya steppe and has a lack of water resources (Morozov, 2014). Although subsurface drainages have been established under most of the New zone, it is far from adequate due to sediment accumulating in the pipes. Consequently, it is likely that any Na salts not discharged through drainages will infiltrate into the shallow groundwater and accumulate in low-lying areas.

Although we did not consider the chemical composition in soil in this study, it has previously been reported that solonchak soils are distributed throughout most of the district, with some calcisols on the eastern side (MAWR, 2003). In addition, the soil in Mirzaabad is defined as slightly saline in the Old zone and moderate-to-severely saline in the New zone (Pankova, 2015). Based on these characteristics, it is expected that calcium carbonate, calcium sulfate and Na salts will accumulate in the soil. Therefore, we can use these characteristics and our results to predict which types and locations of salt accumulation. The accumulated salts possibly originate from irrigation water and groundwater, and our results suggest that the New zone will accumulate Na salts due to the presence of Na in groundwater, whereas the Old zone will accumulate calcium sulfate and calcium carbonate due to the presence of Ca or Mg in irrigation water.

The administrative organizations in charge of the Syrdarya Region plan and execute drainage improvement projects and leaching operations to remediate the secondary soil salinization problems affecting this irrigated farmland. These projects currently prioritize areas with high levels of salt salinization (i.e. high salt concentration). Our results suggest that Na salts can easily accumulate in the New zone, and so it is important to prevent groundwater level rise. Therefore, for sustainable irrigated agriculture, we recommend maintaining the subsurface drainages to prevent highly saline groundwater rising into the plant root zone.

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