ISSN 1341-710X

JIRCAS Working Report No.88

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Preface

Agricultural productivity in Central Asia increased dramatically during the middle of the 20th century due to the large-scale development of irrigated land. The government of Uzbekistan has dedicated additional funding and resources to enable farming in arid and semi-arid regions. However, inadequate water management and poor drainage had led to widespread salinization of soil in Uzbekistan, causing serious damage to agricultural production over a large area.

Several measures can be taken to mitigate soil salinity, including water-saving technologies (e.g., drip or sprinkler irrigation), leaching, flushing, laser leveling, dredging of open drainage systems, installation of sub-surface drainage, and removal of salinized surface soil. Most of these measures, however, involve a high initial cost, which is the main barrier of their application. As a result, the only low-cost measure that is available to farmers is leaching during the winter after crops (e.g., cotton) have been harvested; yet even the efficacy of leaching has declined due to compaction or hardening of soil layers resulting from the long-term use of heavy agricultural machinery. Therefore, affordable and efficient countermeasures are needed to enhance the leaching effect to reduce the salinity.

From 2008 to 2012, the Japan International Research Center for Agricultural Sciences (JIRCAS) conducted research that focused on identifying methods by which farmers could mitigate secondary salinization in the Syrdarya Region of Uzbekistan. As a product, JIRCAS compiled the technologies in "***On-farm Mitigation Measures against Salinization under High Ground Water Level Conditions Guideline***". This guideline was distributed throughout Uzbek regions, where the lands were most severely affected by salinization, and published also in the JIRCAS website.
(https://www.jircas.go.jp/ja/publication/manual_gudeline/28)

From 2013 to 2017, JIRCAS implemented the research project ***"Measures against Farmland Damage from Salinization"*** under the Joint Research Agreement with the Farmers' (or *Fermer*) Council of Uzbekistan. It focused on low-cost drainage technologies such as the 'Cut-drain', developed by the Institute for Rural Engineering, National Agriculture and Food Research Organization (or NARO) in Japan, to improve the efficacy of leaching operation.

In 2017, the information necessary for understanding and implementing this technology was described and compiled into a technical manual titled ***"Shallow subsurface drainage for mitigating salinization"***. This study was conducted under the research project, titled "***Research on Measures against Salinization in Uzbekistan***", which was financially supported by the Ministry of Agriculture, Forestry and Fisheries of the Government of Japan. The manual was translated into Japanese, English, and Russian. An abridged version was also translated into English, Russian, and Uzbek for field use.
(https://www.jircas.go.jp/ja/publication/manual_guideline/mitigating_salinization_en)

This Working Report consists of ten articles, which are not described in the technical manual, but based on the results obtained in the field surveys and laboratory experiments and most of the articles have been already published in scientific journals. The Working Report has two main subjects -- "Water Utilization" and "Mitigation of Soil Salinization". Subject 1 (Water Utilization) deals with the methods to prevent salinization such as water-saving furrow irrigation and the vertical drainage system, and

Subject 2 (Mitigation of Soil Salinization) describes strategies to remediate salinization using the Cut-drain system and the furrow irrigation method.

Finally, on behalf of JIRCAS, I would like to express my gratitude and appreciation to the Farmers' Council of Uzbekistan and the project members of the Scientific Research Institute of Irrigation and Water Problems of the Republic of Uzbekistan. I extend my appreciation to the Ministry of Agriculture, Forestry and Fishery (MAFF), Japan International Cooperation Agency (JICA), and the Japanese Embassy in Uzbekistan for their kind cooperation and meaningful advice during the implementation of the project. To end, I thank all those who contributed to the papers in this Working Report.

Satoshi Tobita
Program Director, JIRCAS

Contents

Current status and problems of the drainage system in Uzbekistan

Yukio OKUDA[1], Junya ONISHI[2], Keisuke OMORI[2], Tetsuji OYA[2], Ayumi FUKUO[3], Rakhmon KURVANTAEV[4], Yulia SHIROKOVA[5] and Vladimir Georgirevich NASONOV[5]

Summary

Agricultural productivity in Central Asia has increased with the development of irrigation. In some regions, continual agricultural land use without adequate maintenance of drainage systems, despite using abundant water in the fields, has led to an increase in groundwater levels and soil salinization rate. The salinization level can be changed by controlling the groundwater level. Important countermeasures practiced in Uzbekistan include lowering high groundwater levels through open drainage, subsurface drainage, and vertical drainage systems. Here, we report the current status and problems of these systems in the Syrdarya Region, Uzbekistan, which is afflicted with serious salinization issues as per field survey results and existing data. Our results clarify that the functioning of the drainage system should be monitored because (1) the bottoms of the open drainage are too undulated to allow smooth discharge, (2) some outlets of the subsurface drainage are under drainage water level or covered with soil, and (3) the current operation style of the vertical drainage is different from the conventional one. Thus, it is important to ascertain the effects of the discharge systems in Uzbekistan.

Keywords

Drainage system, Groundwater, Salinization, Subsurface drainage, Vertical drainage

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1. Introduction

Agricultural productivity in Central Asia has increased with the development of irrigation since the middle of the 20th century. In parallel, the government has dedicated efforts and resources to maintain irrigated land conditions. In some regions of Uzbekistan, continual use of farmlands has resulted in the rise of groundwater levels and salinization rate of the soil because large amounts of water are used in the fields without adequate maintenance of the drainage systems. The salinization level can be changed by controlling the groundwater level. A countermeasure practiced in this region is to lower high groundwater levels via three types of drainage systems: (1) open drainage, (2) subsurface drainage, and (3) vertical drainage.

Japan International Research Center for Agricultural Sciences (JIRCAS) has undertaken several researches on measures against salinization since 2008. A study of the drainage system has been conducted in Yangiobod Water Consumers' Association (WCA) and Axmedov WCA at Mirzaabad District and Bobur WCA at Oq-olitn District, Syrdarya Region, Uzbekistan (**Fig. 1**). The present study reveals the current status and problems of these three drainage systems in a region with serious salinization issues (Okuda et al., 2012).

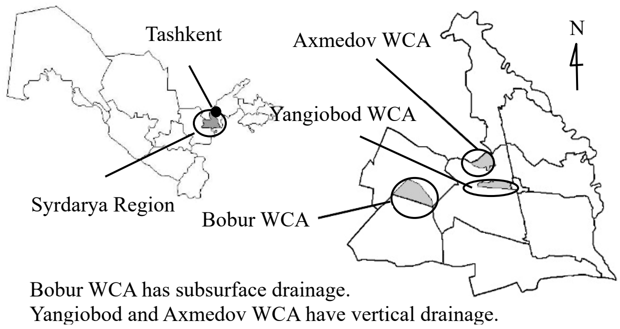
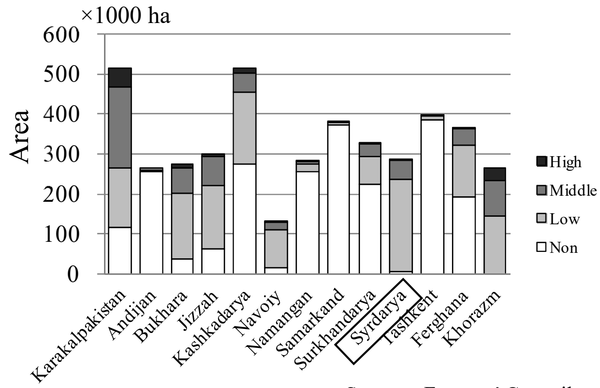


Fig. 1 Location of the study area

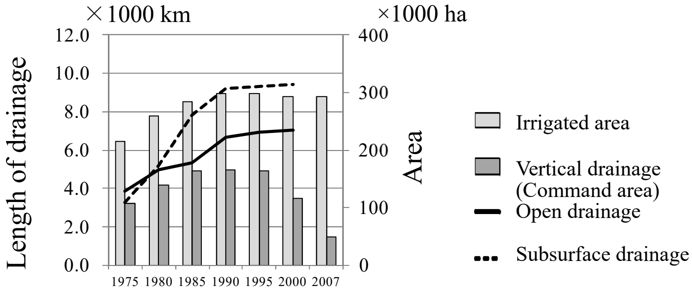
2. Study area

Central Asia has 10 million ha of irrigated land. Uzbekistan alone has 4.3 million ha of irrigated land, and almost half of this area is affected by salinization (Bucknall et al., 2003). Salinization is especially evident in Karakalpakistan, Bukhara, Jizzah, Kashkadarya, Navoiy, Surkhandarya, Syrdarya, Ferghana, and Khorazm (**Fig. 2**). The Syrdarya Region is located in an arid zone called as the "Golodnaya (Hungry) steppe." Here, precipitation is concentrated between the winter and spring seasons (average precipitation rate, 325 mm year^{-1} in the past 10 years). The Syr-Darya river, the main resource for irrigation, flows along the east edge of this region. Approximately 300 thousand ha of land has irrigation and drainage systems in 2007 (**Fig. 3**), and almost all the irrigated land is salinized. Hydro-Geological Melioration Expedition (HGME) is in charge of executing measures against salinization, including monitoring of groundwater level, water quality, and soil salinity and recommending the necessary actions to the concerned organizations. The Department of Pump, Electricity and Communication is in charge of vertical drainage.



Sources: Farmers' Council

Fig. 2 Region-wise area of salinization (2011)



Sources: Research Institute of Irrigation and Water Problem

Fig. 3 Changes in the development of drainage system

3. Materials and methods

Data for this study were obtained via field surveys and interviews conducted between 2011 and 2013. Topographical survey, observation of drainage discharge, groundwater level, and electric conductivity (EC) were conducted to study the open and subsurface drainages. Salinity of water and soil sampled at the survey area was analyzed by the Institute of Irrigation and Water Problem (RIIWP) and Gulistan State University. To understand and analyze the current status of drainage systems, interviews for collecting the data/information were implemented with the assistance of RIIWP, Farmers' Council, HGME, and Department of Pumping, and Electricity and Communication in the study area.

4. Current status and problems

4.1 Open drainage

The open drainage consists of a branch drainage (Inter-farm Collector) that connects WCAs, drainage canals (Intra-farm Collector) built between the farmlands in a WCA, and the other small drainage canals. The drainage system requires a drainage depth at which groundwater can flow out. In the survey area, depth of the collectors was approximately 2–4 m, with depths of small canals < 2 m. HGME undertakes executive responsibility for collectors and performs cleaning on the governmental budget distributed to

HGME. Small drainage canals near the border of fields with different water uses are constructed by famers or others. As per the data from RIIWP, length of the collectors increased with the increase in the area of irrigated land until 1990, after which this practice was not extended. According to the interviews, performance of the collectors has declined by sedimentation each year. Therefore, repair and renewal measures for the collectors are critical.

Observation of discharge and water salinity downstream of a collector in Bobur WCA showed effective salinity run-off in March and April. However, lesser salinity run-off was detected in October and December, despite an abundant discharge (**Fig. 4**). Flowing of the irrigation water into the collector is wastage of water. Results of a topographical survey indicated that the collector's bottom is at 2–3.5 m depth to the field surface. The width of the collectors, including both sides of the slopes, is 20–30 m. Collapses of slopes and thick growth of weeds contribute to sedimentation and stagnation of drainage water. This inadequate maintenance causes an increase in the drainage water level, because of which the groundwater is unable to flow out to the collector. It is also easily influenced by water use in the field surroundings.

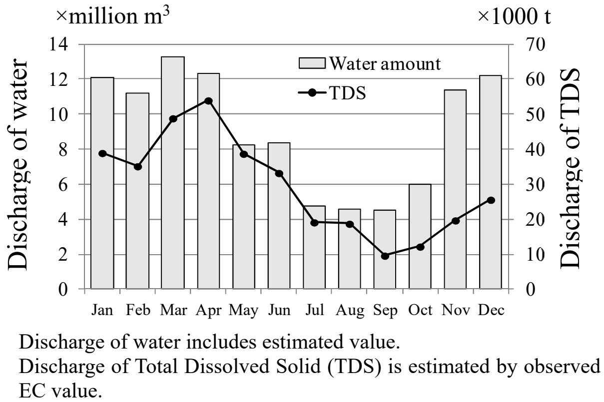


Fig. 4 Discharge and TDS in a collector

4.2 Subsurface drainage

In Bobur WCA, subsurface drainage pipes were installed at depths of 2.5–3.0 m, and the spaces between the pipes are approximately 210–250 m. There were four pipes in the survey field: three (Nos. 1, 2, 3) were near the research field and one (No. 4) was present 1 km to the north. The outlet of No. 1 was lost; that of No. 2, covered by soil; that of No. 3, observed under drainage water; and that of No. 4, exposed above the drainage water level (although that of No. 4 was supposed to be covered with slope soil eventually). In June 2012, the height of outlets 2 and 3 were 1.1 m and 0.3 m below the drainage water level, respectively. After removing the covering soil and water near the outlet, discharge quantity from each outlet was measured. Differences were noted among the discharges for Nos. 2, 3, and 4, with less than one-twelfth difference for Nos. 2–4 and one-third difference for Nos. 3 and 4 in July 2012 (**Fig. 5**); this gradually reduced to almost zero and then one-forth by August, respectively, while the discharge quantity for No. 4 remained unchanged. The outlet

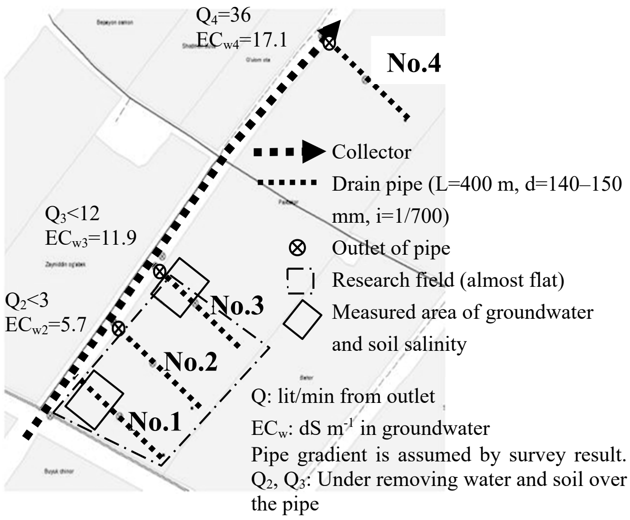
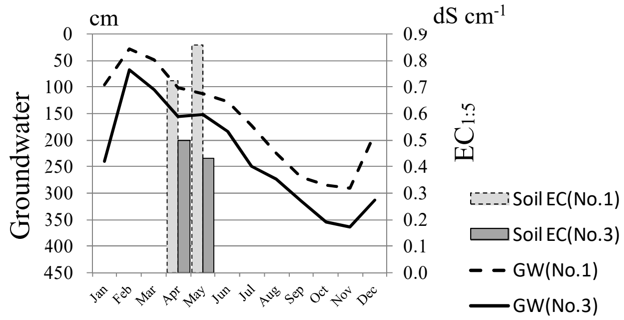


Fig. 5 Discharge and EC (July, 2012)

condition has seriously affected groundwater discharge. In this study, the groundwater level was observed to be higher in February and March 2012, descending gradually until September and temporally maintaining its level during irrigation, followed by rising again from autumn onwards. The groundwater level near No. 3 was 0.5–1.7 m lower than that near No. 1. Soil salinity ($EC_{1:5}$) of No. 3 was approximately 30–50% lower than that of No. 1 in April and May 2012 (**Fig. 6**).



EC value shows average in a layer of 0–100 cm near collector.
Groundwater level (GW) shows average of near collector.

Fig. 6 Groundwater and soil salinity ($EC_{1:5}$) (2012)

Outlet status affects groundwater level and soil salinity. The system has to keep the outlet above the drainage water level to expose it. The outlet needs to be protected to maintain its function.

4.3 Vertical drainage

The vertical drainage system controls groundwater via wells equipped with pumps. According to the query results of JIRCAS to RIIWP and the Department of Pump, Electricity and Communication in the study region, the first phase of development was set from the 1920s to the 1960s for research, testing, and establishment of the system; the second phase was set for intensive construction from the 1960s to 1995; and the last phase was set for operation 1995 onwards. The number of operations then reduced from 1995. In 2013, 450 vertical drainages were listed in the operation list of the department. Few overlapping areas were noted with subsurface drainage. According to the technicians of the department, the beneficial area of vertical drainage in this area would be approximately 100 ha. Therefore, a new vertical drainage is planned to be constructed within a distance of approximately 1 km from the existing one. The department pointed out a decline in the pumping potential due to degradation of the wells. RIIWP showed that pumps should operate continuously from December to February and during the season of high groundwater levels between March and August. However, currently, the operation pattern of vertical drainage is different between the investigations and results of data analysis on electric power consumption of the department. The annual groundwater level was also different between the investigation and field survey. According to the interviews, 80 wells were present in 11 out of 17 WCAs in the Mirzaabad District. Assuming that the influence radius is 500 m, the benefit circle does not overlap (**Fig. 7**). The number of operating wells was 49 (61%), 67 (84%), and 65 (81%) in 2011, 2012, and 2013, respectively, as per the data of electric power consumption. The reasons for no operation were explained by the department to be: under inspection and maintenance, theft of electric equipment, no request or necessity of operation near abandoned lands, and safekeeping in other places against theft. In these 3 years, the total consumption was small between the winter and spring seasons when the groundwater level is the highest. However, the total consumption was very high in summer. Thus, the difference in consumption between the summer and winter seasons was 3.5 times. Based on the request or direction by the HGME, the department takes a monthly decision of short-listing operational places and periods in accordance with the budget. The department also considers requests from farmers. The requests of operation generally increase in summer when the evaporation rate is high, causing increased salinization and shortage of irrigation water. In case of no salinity issue in the groundwater, the vertical drainage can be used for irrigation along with river water.

Currently, the performance of the vertical drainage system varies with method of operation. A new operation plan should be considered for optimizing the advantages of the system for maximum effect. In addition, the management approach should improve the functions of the system in line with the new data obtained.

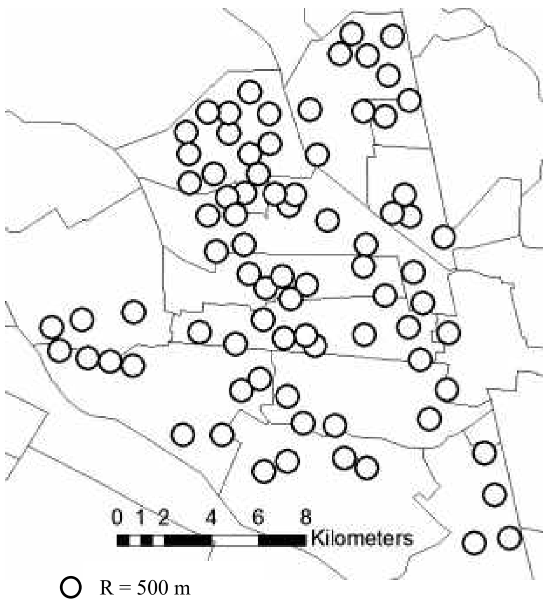


Fig. 7 Location of vertical drain in Mirzaabad district

5. Conclusion

Some collectors in Uzbekistan face sedimentation and malfunctioning drainage-water flow, which contributes to increasing salinity in agricultural lands. Some outlets of subsurface drainages in collectors are placed below the drainage water level or are covered with soil, leading to a decline in groundwater discharge and hindrance to salinity correction in the soil. Cleaning of the collectors requires excavator machines, and farmers and WCAs cannot not use these machines because of budget limitation. Thus, government-supported cleaning projects can serve as appropriate measures. To achieve maximum benefits, surveys of collectors and outlets for subsurface drainages are necessary. The surveys should identify collectors for sedimentation removal. In areas with subsurface drainages, it is important to expose the outlet and ensure that it remains above the drainage level. In case of shallow collectors with repair difficulties, a possible suggestion is to decrease the salinity smoothly in the field by improving field drainage conditions, such as using shallow subsurface drainage. The current vertical drainage system has a varied number of wells and a different operation pattern than the conventional one. Studies on the effect of this current system are limited. It is therefore important to clarify the effect of the current operation system to design an efficient and economical operation system.

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*The above article was reprinted from “Journal of Arid Land Studies, Vol. 25, No. 3, pp. 81-84 (2015)” by courtesy of the Japanese Association for Arid Land Studies.

Subject 1: Water Utilization

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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[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.

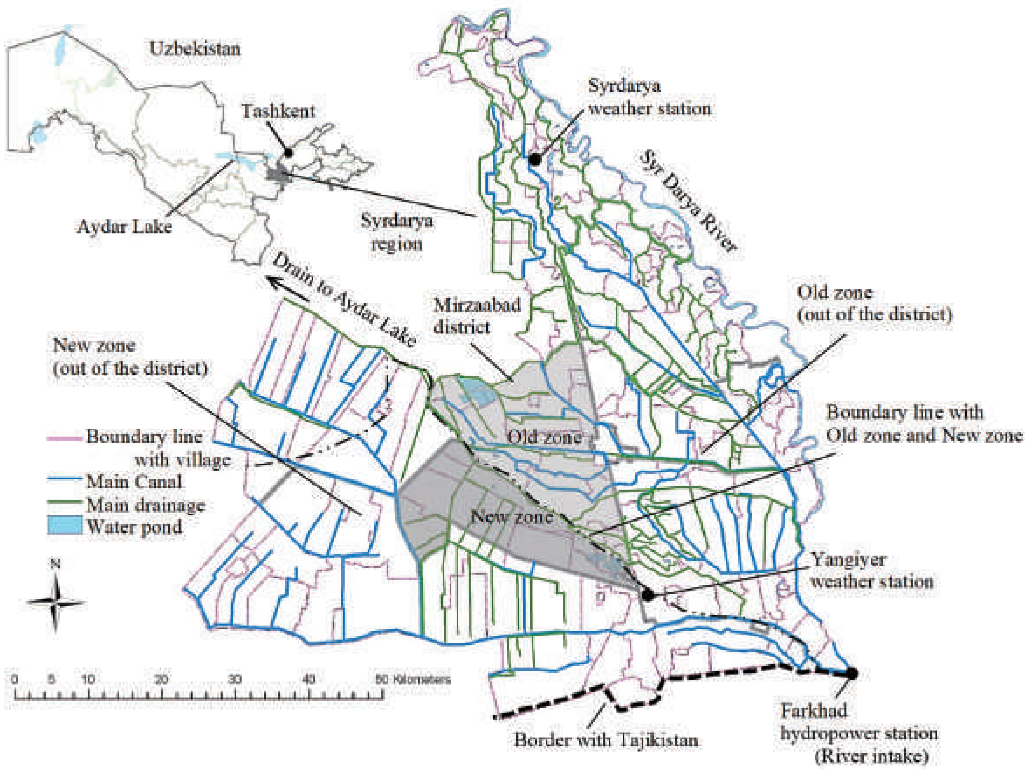

Fig. 1 Survey site and irrigation - drainage network in Syrdarya Region

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.

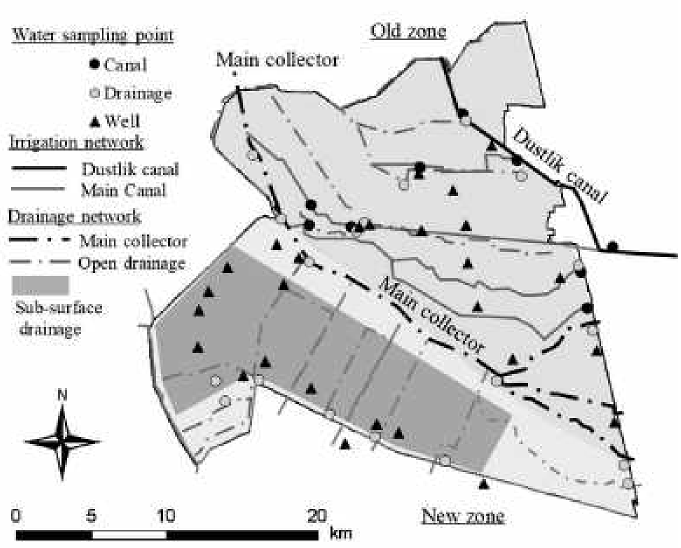

Fig. 2 Irrigation – drainage network and water sampling points in the Mirzaabad district

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 water	Groundwater	
	Water sources	Canal 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).

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

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).

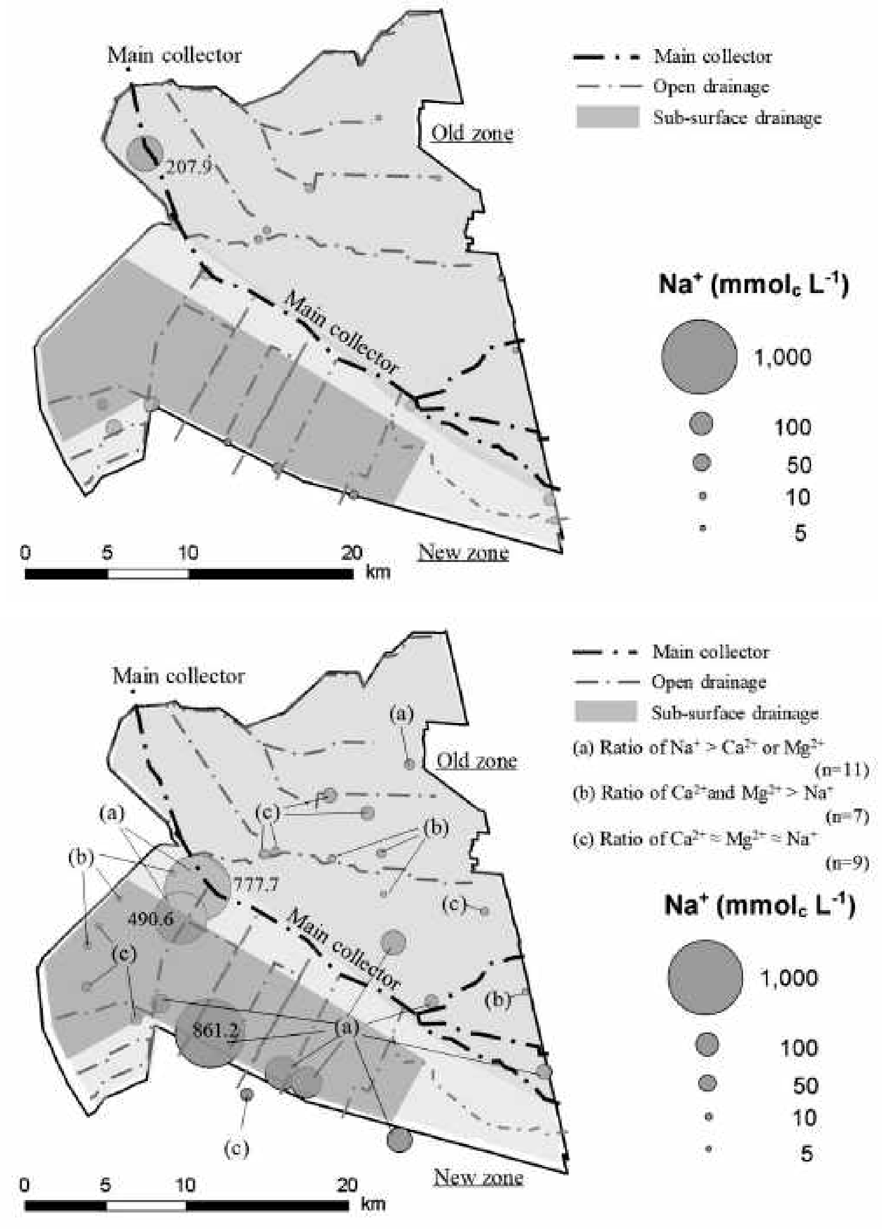

Fig. 3 Distribution of Na^{+} concentration for drainage water (upper) and groundwater (lower) at the sampling points

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**).

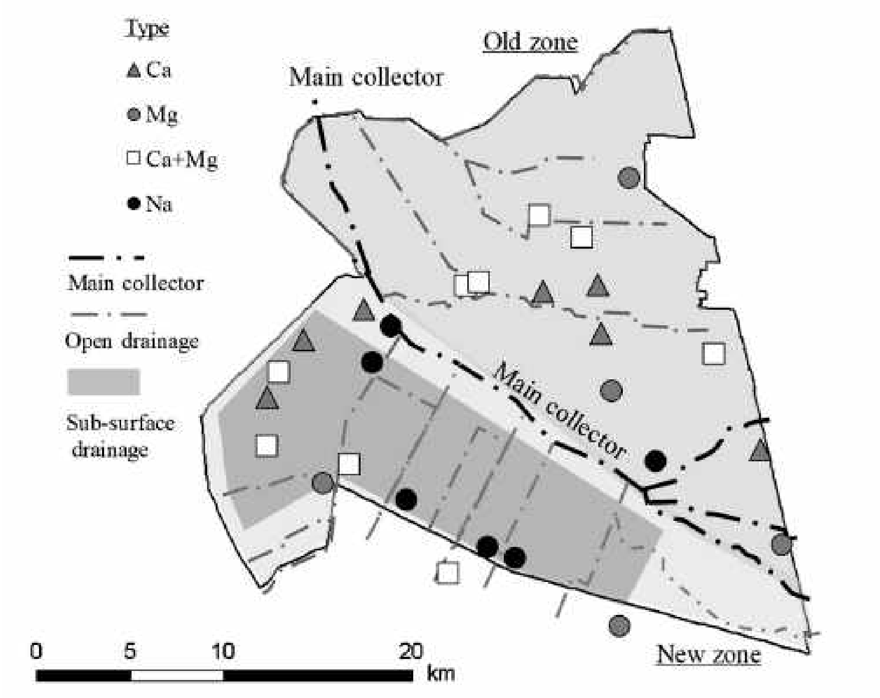

Fig. 4 Distribution of the four type salts (Ca, Mg, Ca+Mg and Na) in groundwater.

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**.

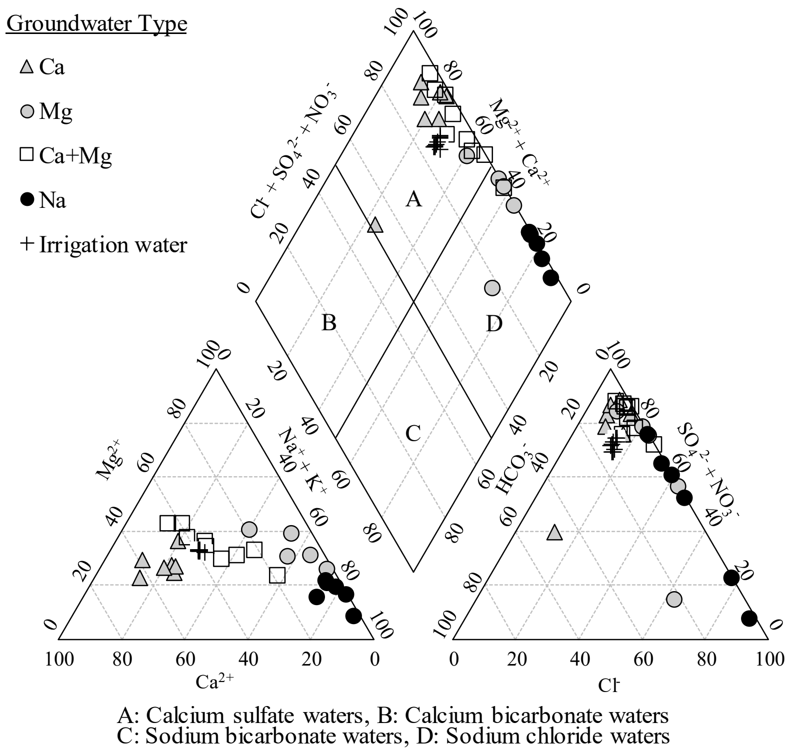

Fig. 5 Piper diagram of groundwater and irrigation water.

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.

Acknowledgments

This study was conducted under the research project "Research on Measures against Salinization in Uzbekistan" financially supported by the Ministry of Agriculture, Forestry and Fisheries of the Japanese Government. The authors gratefully thank Dr. Akira Hirano and Dr. Ayumi Fukuo for technical support in creating the GIS map.

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*The above article was reprinted from “Sand Dune Research–Vol. 64, No. 3, pp. 101-111 (2018)” by courtesy of the Japanese Society of Sand Dune Research.

Actual Condition of Vertical Drainage for Farmland Salinization in the Republic of Uzbekistan

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Summary

In irrigated agricultural area of Central Asia, drainage channels, subsurface drainage, and vertical drainage have been constructed as countermeasures for soil salinity. However, these drainage functions have worsened due to lack of regular maintenance. In particular, the number of vertical drainage facilities is drastically reduced, and the availability of operating facilities has decreased. This report studied whether vertical drainage affects the groundwater level by using monitoring results and analyzing them at area-wide of Water Consumers' Association (WCA).

As a result, there was no clear relationship between the operation of vertical drainage and groundwater level. Although vertical drainage affected the location 500 m away, it is not considered to greatly influence WCA. As the operation ratio of vertical drainage becomes very low, we need to reconsider the plan of groundwater level control by vertical drainage within each WCA or interrelated WCAs. It is also clear that the relationship between groundwater levels and the fluctuation of salinity levels has not been understood at WCA. Cooperation among the related local government organizations and WCAs needs to be strengthened to find a solution to the salinity problem with monitoring and countermeasures. This needs to focus on the measures against salinization except for the measures against high groundwater level.

Keywords

Vertical drainage, Groundwater, Salt-accumulation, Soil salinity, Syrdarya region, WCA

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1. Introduction

Large-scale irrigation development has been carried out in the five Central Asian countries of Uzbekistan, Kazakhstan, Kyrgyzstan, Turkmenistan, and Tajikistan since the 1960s, with the Amu Darya River and the Syr Darya River, which flow into the Aral Sea being used as the main water resources. With the development of irrigated agriculture, waterlogging and salt accumulation has occurred due to excessive irrigation and inadequate drainage facilities. As a counter measure, salt removal operation has been implemented by drainage improvement projects and leaching works.

By the 1990s, a drainage network of approximately 200 thousand km was developed in these five countries, with the provision of 48 thousand km of subsurface drainage and the construction of 7,700 vertical drainage wells (Dukhovny et al., 2005). However, new drainage facilities have not been constructed and regular maintenance of the current drainage facilities has not been adequate since those countries became independent of the Soviet Union in 1991. As a result, these drainage functions have worsened. In particular, the number of vertical drainage facilities is drastically reduced, and the availability of operating facilities has decreased.

The Japan International Research Center for Agricultural Sciences (JIRCAS) was conducting studies on measures for mitigating salinization through groundwater control in the Syrdarya Region of the Republic of Uzbekistan (**Fig. 1**). This is an arid and semi-arid region of Central Asia which has the highest salt concentration in the soil. Our studies have focused on the serious salt accumulation area of Mirzaabad district in the Syrdarya Region. This report is based on data for the Mirzaabad, which was obtained from relevant organizations regarding the analysis of the relationship among the operation ratio of vertical drainage, groundwater fluctuation, and soil salinization.

2. Materials and methods

2.1 Vertical drainage data

Vertical drainage is a water pumping facility with wells to control the groundwater level. Based on boring surveys, the wells are mined down to the clear water aquifer. The wells in the Syrdarya Region were drilled down to a depth of 30 to 120 m. The facilities are operated and managed by the Department of Pumping Station, Energy and Communications (UNES: Russian abb.), a local organization of the Agriculture and Water Resources of Uzbekistan Government. A record of monthly electricity consumption from 2011 to 2013 was obtained from the UNES for all vertical drainages managed in the Mirzaabad. We confirmed the locations of vertical drainage and their management directly by field surveys. We also obtained other information about vertical drainage from the Research Institute of Irrigation and Water Problem (RIIWP) surveys.

As a case study, one vertical drainage facility (depth: 52 m, strainer pipe position: 28 to 44 m) was selected in 2014, and observation wells at groundwater level were installed at 60, 100, 250 and 500 m away from the vertical drainage well. In the observation wells, we measured the depth of groundwater level (measuring groundwater potential by open only at the bottom, depth of 35 m) and the surface groundwater level (full open pore, depth of 5 m) and recorded the fluctuation of the groundwater level during vertical drainage operation.

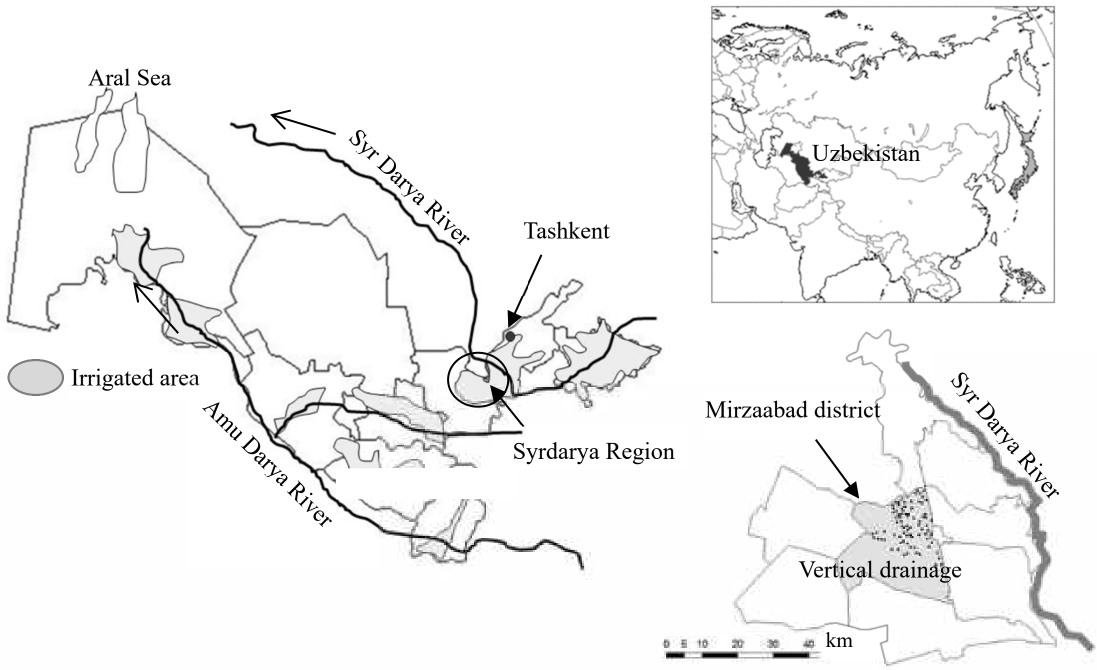

Fig. 1 Study area

2.2 Monitoring data of groundwater and soil

The groundwater level and salinity of groundwater and soil are monitored by the Hydro-Geological Melioration Expedition (HGME), which is a local organization of the Ministry of Agriculture and Water Resources of Uzbekistan. The HGME developed the data of the monitored area, sorted it into several levels, and then mapped the values in each level. Previously, the drawing on the map was conducted by hand, but advanced mapping technology of Geographic Information Systems (GIS) are being implemented for the Mirzaabad in Uzbekistan.

In this survey, GIS area data of groundwater level and salinity of groundwater and soil from April 2010 to March 2013 were obtained as well as all observational data for the observation well regarding the groundwater level of 2012.

3. The current condition of the survey area

3.1 Facility situation of vertical drainage

Construction of vertical drainage in Uzbekistan started in the early 1960s, and the number of facilities peaked in the middle of the 1990s. A number of facilities have not been updated and well maintained since that time, and the number of facilities is decreasing. The number of facilities in 2002 dropped to 79% in Uzbekistan nationally compared to the peak and also 38% in the Syrdarya Region. In addition, electricity consumption has also begun to decline since the 1980s, to 14% of its peak in the region (**Fig. 2**).

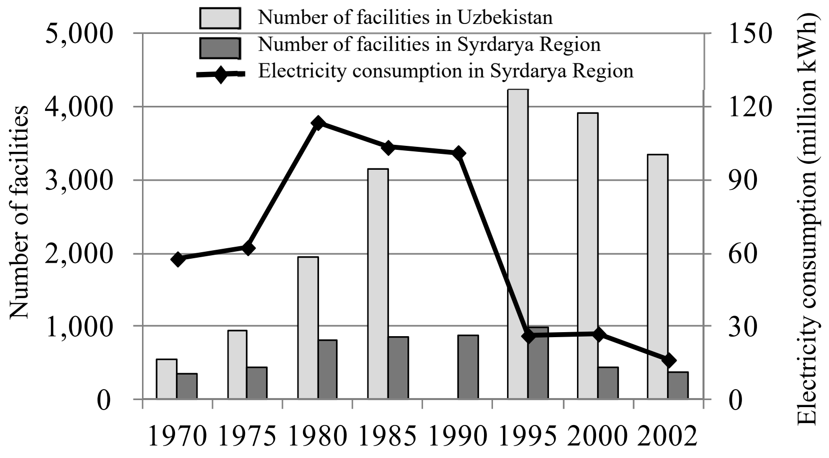

Fig. 2 Decline in the number of facilities and electricity consumption

It is reported that one vertical drainage facility covers an area of approximately 100-150 ha, and there are 373 sites in the region, where it comprised approximately 50 thousand ha in 2007. However, the annual operation rate is only 20%. According to UNES, the renewal of facilities is being promoted as one of the farmland improvement measures projects and in 2013, the number of facilities had reached 450. Based on the results of groundwater and soil monitoring by the HGME, but only when specifically requested by the farmers, the operation of vertical drainage is to be conducted. When examining the amount of electricity consumption by month, there is a peak in summer, which plays a role as supplemental water for the irrigation period.

There were 17 Water Consumers' Associations (WCAs) in the Mirzaabad district, which were surveyed in 2012. Vertical drainage facilities which covered 11 WCAs were located on the eastern side of the region. The number of facilities was 80. The number of facilities per one thousand ha, where a WCA has a piece of irrigated farmland, is 3.6 on average, 6.7 at maximum, and 1.1 at minimum, which is a large variation in the number of facilities. While 80 locations can be seen in the consumption of electricity and 95% of facilities were operating over three years from 2011 to 2013, some facilities have been in operation only on a trial basis or have not been in operation for more than one year. The consumption of electricity depends on each facility.

In the Syrdarya Region, the combination of salinity area rate and groundwater salinity is being researched to determine the target groundwater level for vertical drainage. According to RIIWP, in order to avoid the risk of salinization, it is preferable that the target groundwater level is deeper than 1.9 m in April, and deeper than 3.5 m in August and September.

3.2 Monitoring of groundwater level

There are 2,030 observation well sites run by HGME in the Syrdarya Region. Within the area, 284 observation wells exist in the Mirzaabad district, meaning one location per 140 ha. The groundwater level is measured by HGME technical workers every ten days, who also take a sample and measure the salinity of groundwater from the observation wells in April, July, and October. The monitoring results are divided into five stages of groundwater level and salinity (**Table 1**). This information is sent to UNES to control the groundwater level and is also applied for implementation of the leaching in December and January in winter and further leaching.

Table 1 Groundwater level and salinity in the Mirzaabad district (April 2012)

Groundwater level (m)	0.0-1.0	1.0-1.5	1.5-2.0	2.0-3.0	>3.0
Area (thousand ha)	1.9	5.4	14.0	17.6	2.2
Salinity (g L^{-1})	0-1	1-3	3-5	5-10	>10
Area (thousand ha)	0.0	7.0	20.9	10.9	2.2

3.3 Monitoring of soil

Measurements of soil salt concentration are taken in April and October each year. Measurement points differ, depending on the land use and the time of year. These measurements were taken at 1,570 locations (one location per 26 ha) in 2012. For this, HGME technical workers travel around the field and measure EC values at three levels of depth (0-30 cm, 30-70 cm, and 70-100 cm) using a soil insertion type EC meter. This EC meter was developed by RIIWP and converted to EC_e (soil salinization levels expressed as electrical conductivity (dSm^{-1}) by saturation extraction) values from the measured salinity of the interstitial water of the soil and the temperature of the ground. According to the FAO standard, No salinity (EC_e <2), Low (EC_e 2 to 4), Moderate (EC_e 4 to 8), High (EC_e 8 to 16), and Extraordinal High (EC_e > 16) salinity (FAO, 2002).

In the Syrdarya Region, soil salinity maps are created using the same standard values and divided into four levels of No salinity, Low, Moderate, and High. High includes High Intensity. The map indicates that areas greater than Mild in Uzbekistan is 49%, in the Syrdarya region is 98%, and those in almost all Mirzaabad district are 100% (**Table 2**). Information on soil salinity will also be sent to UNES, together with groundwater data, and they will be used to make a plan of future salt damage counter measures.

Table 2 Soil salinity level

(unit: thousand ha)

	No salinity	Low	Moderate	High
Uzbekistan (2011)	2,195.5	1,361.0	624.6	124.0
Syrdarya Region (2011)	4.6	231.7	47.1	3.6
Mirzaabad district (2012.4)	0.1	22.3	17.8	0.9

4. Results

4.1 Vertical drainage and groundwater level

4.1.1 Changes in groundwater level of WCA

We verified that vertical drainage controls the groundwater level by dividing areas into three categories: (a) operation of vertical drainage (11WCAs: 22 thousand ha), (b) no vertical drainage (2WCAs: two thousand ha), and (c) no vertical drainage but using the subsurface drainage (4WCAs: 17 thousand ha). We then compared these areas and found that the groundwater level in each area tends to be lower from May to October, then increases from October to February. When the vertical drainage operation peaked during June to August, the groundwater level in the area (a) did not show a particularly significant downward trend compared with the (b) and (c) areas (**Fig. 3**).

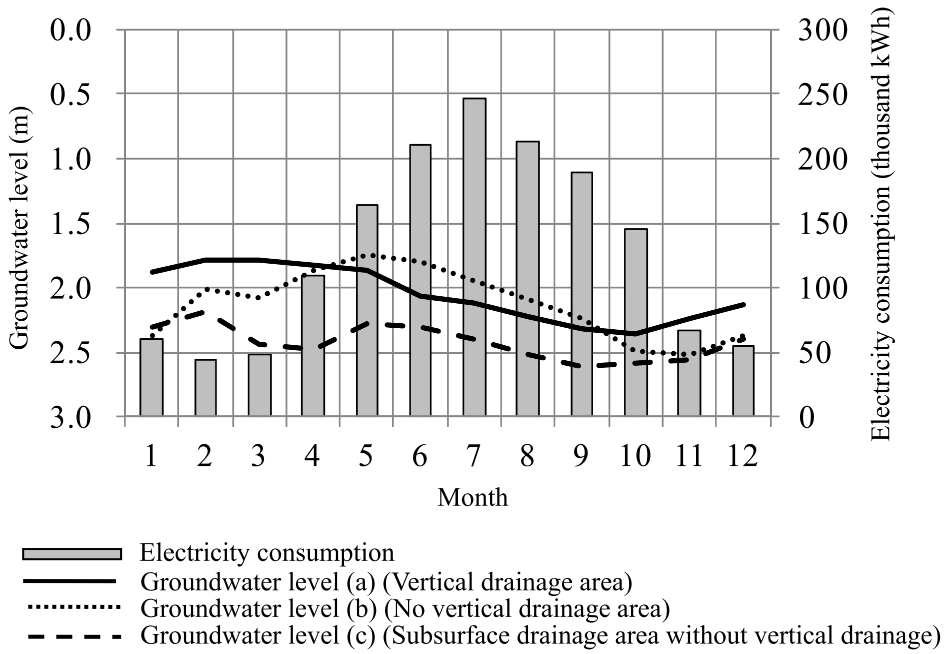

Fig. 3 Changes in groundwater level due to differences in drainage conditions (2012)

When comparing electricity consumption per hectare with annual average groundwater level, the low groundwater level in the WCA area showed a trend of increased electricity consumption (**Fig. 4**). The vertical drainage has not conspicuously lowered the groundwater level in the WCA area. In addition, it is assumed that the operation is being prioritized in the WCA areas where the groundwater level is high.

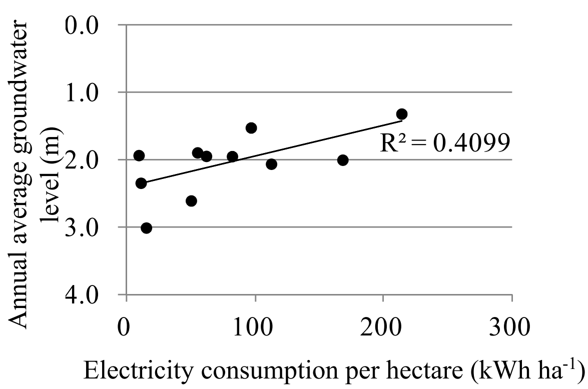

Fig. 4 Electric consumption trend in 11 WCAs

The reason we cannot see the large fluctuation of groundwater level may be because the number of vertical drainage facilities in the WCA farmland is small and the operating ratio is low (a short period of pump operation hours). The causes of low utilization rates are delays in maintenance repair, frequently occurring power outages, expensive electricity bills, and theft.

4.1.2 The fluctuation of groundwater level in the facilities

With the WCA standard we could not confirm, with clarity, the effectiveness of vertical drainage and we therefore surveyed the cases of one vertical drainage operation. For example, the fluctuations of groundwater level at nearby facilities were observed for 46 days in 2014 between October 26th and December 11th. During pumping, the groundwater level of the observation well installed in the deep section could be observed 60 m from the vertical drainage facility. The groundwater level was influenced within 10 minutes and it repeatedly descended and ascended, according to the operation and stop of the pump. At 500 m away from the facility, the observation well showed subtle fluctuations within 30 minutes.

Normally the groundwater level starts to rise from October, and we could therefore see the rise in every observation well location. The water level of 60 m away from the facility raised the least at both the high deep layer and surface layer from our observation date to another date in December. It showed only 2 cm difference in rise of the deep layer and 3 cm of surface layer, compared with those 500 m away from the facility (**Fig. 5**).

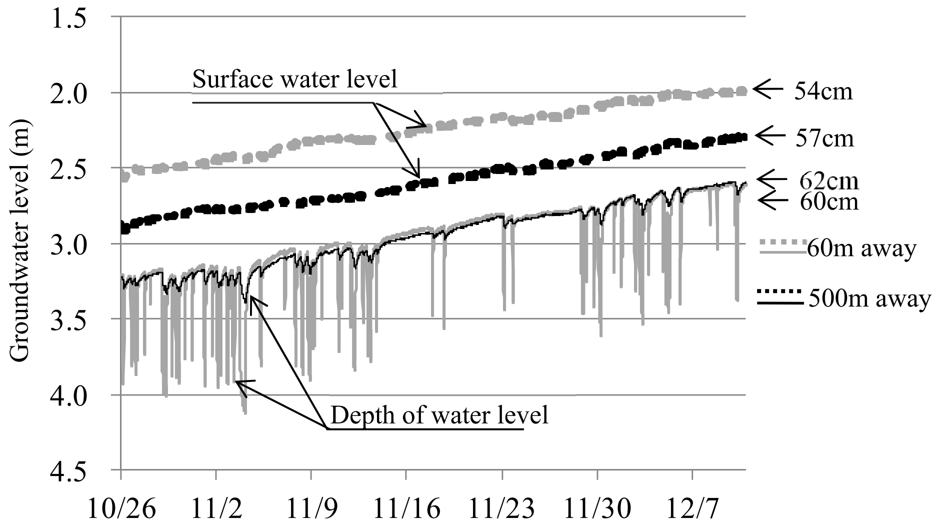

Fig. 5 Changes in groundwater level during vertical drainage operation

When we observed the vertical drainage alone, even if the groundwater level in the deep layer was 500 m away, the effect could be seen, but the influence on the surface layer was small. It was less affected because the survey period was the rise time of groundwater level in winter and it was the short period. Despite the low effect of surface water control, there was a possibility that vertical drainage was used during this period. The efficacy of fluctuation was not adequately seen at the WCA areas, and we therefore need to focus on the necessary timing and areas of vertical drainage operation and then consider aspects of implementation such as concentrate and consecutive operation period.

4.2 Variation of soil salinity of WCA

We analyzed the relationship between the variation of soil salinity and groundwater level at the chosen 17 locations of WCA from April to October 2012 and also classified the soil salinity class of HGME. The salt accumulation in soil was classified as: no salinity = 1, low = 2, moderate = 3, and high = 4. The weighted average by the area according to the category was taken.

As a result, the evaluation of the soil salinity rating changed from 2.48 in April to 2.79 in October. Therefore, it had reached 113% fluctuation ratio at 100% as of April. The maximum concentration rate was 132% and the minimum rate was 98% at each WCA location. Some locations did not show increasing numbers despite the high soil salinity season. The groundwater level classified by WCA until just before October was considered to be affecting this rate of change compared with the average groundwater level from April to September of (a) operation of vertical drainage, (b) no vertical drainage, and (c) no vertical drainage but using the subsurface drainage, mentioned above. However, there was no explicit correlation found (**Fig. 6**).

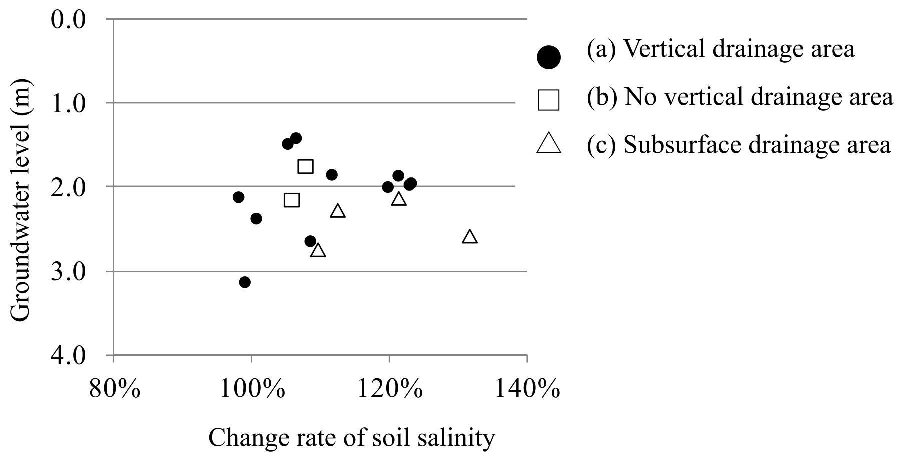

Fig. 6 Rate of change of soil salinity and groundwater level (2012)

Even if the groundwater level is deep, the soil salinity may be highly concentrated, and if the groundwater level is shallow, the soil salinity may not change. This result might be affected by the influences of not only groundwater level or salinity but also soil composition, water control technology by WCA, drainage function, type of salt, the land use situation (amount of abandoned cultivated land), and other factors. Therefore, such uniform measures taken by WCA might be less effective in the field.

In order to ensure that the effects of salinity measures, including vertical drainage are realized, it will be necessary to clarify these factors, scrutinize them well, and then strengthen the coordination between monitoring and counter measures.

5. Conclusion

The Syrdarya Region is in the Republic of Uzbekistan which is an irrigated agricultural area of Central Asia. Through the monitoring of groundwater and soil, drainage improvement work and leaching are planned so as to implement counter measures against salinization. This report studied whether vertical drainage affects the groundwater level by using monitoring results and analyzing them at WCA level. There was no clear relationship between the operation of vertical drainage and groundwater level. Although vertical drainage affected the location 500 m away, it is not considered to greatly influence WCA.

As the operation ratio of vertical drainage becomes very low, we need to reconsider the plan of groundwater level control by vertical drainage within each WCA or interrelated WCAs. It is also clear that the relationship between groundwater levels and the fluctuation of salinity levels has not been understood at WCA. Cooperation among UNES, HGME, and WCA needs to be strengthened to find a solution to the salinity problem with monitoring and counter measures. This needs to focus on the measures against salinization except for the measures against high groundwater level.

We courteously acknowledge the substantial cooperation for this study from RIIWP, HGME, UNES, and the Farmer’s Council of Uzbekistan.

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Water-saving Effect of Simplified Surge Flow Irrigation on Irrigated Farmlands in Arid Areas - A Case Study in the Republic of Uzbekistan -

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Summary

In some parts of irrigated farmlands in arid areas, decreasing crop productivity caused by secondary salinization due to excessive irrigation and poor drainage has become a serious problem. Water saving is required in such areas, but it is not easy to shift to a more efficient irrigation method due to lack of funds and difficulty in procuring equipment. For these reasons, furrow irrigation, although causing large infiltration losses, is still being widely practiced.

In order to save water in furrow irrigation through the use of a method which can be easily adopted by farmers, a simplified Surge Flow irrigation method (hereinafter referred to as 'simplified SF'), which is a simple version of the regular Surge Flow method (hereinafter referred to as 'SF'), was contrived. In SF, water is applied intermittently, about 4 times by using pipelines and valves, to obtain water-saving effect. On the other hand, in the simplified SF, a single furrow irrigation (conventional furrow irrigation) is just divided into two. In this research, the water-saving effect of the simplified SF was verified on irrigated farmlands exhibiting remarkable secondary salinization in Uzbekistan. In the furrow infiltration test, the cumulative infiltration at 60 minutes after the start of flooding, in the soil that has been supplied with water before one day, decreased by 9.5 mm compared with that of the dry soil; and the basic intake rate also decreased to less than 50%. In the comparative irrigation test between the conventional furrow irrigation method and the simplified SF on 100 m furrow (slope: 1/800), the speed of water advance during the second water supply by the simplified SF increased, and the total duration it took for the irrigation water to reach the end of the furrow (irrigation time) was 6,026 seconds (about 100 minutes); this was 742 seconds (about 13 minutes) shorter than that of the conventional method, which had an irrigation time of 6,768 seconds (about 113 minutes). These results therefore showed that the simplified SF could reduce the amount of water supplied to the furrow and the amount of oversupplied water by 11% and 15%, respectively.

This present study demonstrates the potential of the simplified SF as an effective water-saving method in the developing countries facing water management problems. It should be noted, however, that the water-saving effect of the simplified SF was lower than the 21% obtained with the use of regular SF in Fergana, Uzbekistan. In addition, stagnation of irrigation water due to the unevenness of furrows may have affected the water-saving effect of the simplified SF. Therefore, to deal with the future challenges concerning the application of the simplified SF in the field, it is necessary to consider optimal furrow length, as well as measures to suppress the influence of uneven furrows.

Keywords Salt accumulation, Furrow irrigation, Water-saving irrigation, Simplified Surge Flow irrigation method, Republic of Uzbekistan

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1. Introduction

1.1. Background

Irrigated agriculture in arid land, especially in developing areas where appropriate water management has not been conducted due to inadequate facilities and workforce, the negative effect by salt accumulation has become a serious problem. The United Nations Food and Agriculture Organization (FAO) estimates that approximately 1.5 million ha of irrigated farmland is abandoned every year due to waterlogging and salinization (Tony, 1995). If the abandonment of cultivation continues at this speed, in 50 years approximately 50% of the current irrigated farmland will be abandoned and the food supply capacity is expected to be halved (Kitamura, 2016).

This type of salt accumulation (secondary salinization) is remarkable in Central Asia where the development of large-scale irrigation occurred during the Soviet Union era, greatly contributing to agricultural production. Plain soils in Central Asia were originally rich in salts and there is a high risk of secondary salinization associated with irrigated agriculture (Shirokova and Morozov, 2006). The Republic of Uzbekistan, which played a role in cotton production during the Soviet Union era, has the largest salt affected farmland area (**Table 1**) (Karen, 2013). In this study, salt-affected farmland is defined as farmland where the electrical conductivity of the saturated extract of soil (EC_e) is 2.0 dSm^{-1} or more.

Agricultural production in Uzbekistan is conducted by a management entity with a legal persona called "*Fermer*", which are provides farmland owned by the country by way of long-term loan contracts (Onishi, 2012). The area of farmland is several dozen ha, and crop cultivation is conducted with furrow irrigation.

Table 1 Salinized area of the total area under irrigation in Central Asia

Country	Area equipped for irrigation		Area salinized by irrigation		
	Year	ha	Year	ha	(%)
Uzbekistan	2005	4,198,000	1994	2,141,000	51
Kyrgyz	2005	1,021,400	2005	49,503	5
Tajikistan	2009	742,051	2009	23,235	3
Kazakhstan	2010	2,065,900	2010	404,300	20
Turkmenistan	2006	1,990,800	2002	1,353,744	68
Total		10,018,151		3,971,782	40

Source: Irrigation in Central Asia in figures (Karen, 2013, FAO Water Reports 39, pp 68)

As one of the water-saving methods based on furrow irrigation that reduces downward infiltration, there is Surge Flow irrigation (SF) (Walker, 1989). SF is a method used to reduce the permeability of furrows by stepwise water supply reducing the downward infiltration loss (**Fig. 1**). Four physical processes cause the reduction in infiltration: 1) consolidation, owing to soil particle migration and reorientation, 2) air entrapment, 3) redistribution of water, and 4) channel smoothing (Mitchell and Karen, 1994). In addition, the reduction of furrow permeability by first irrigation makes the water advance speed of irrigation after the second irrigation increase and can be expected to shorten the irrigation time.

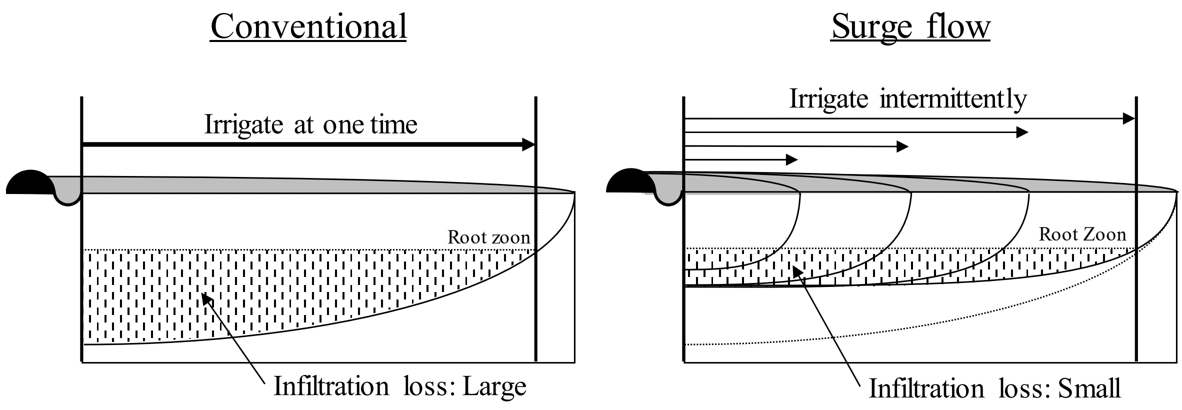


Fig. 1 Concept of Surge Flow irrigation

SF was developed and introduced in Bulgaria in the 1970s, and its introduction was attempted in Kyrgyzstan during the Soviet era. However, it did not reach widespread use. After that, it became widely used in the United States from around the 1980s, and became a worldwide technology (Horst et al., 2005). Horst et al. (2005) conducted an experiment at a cotton field in the Central Fergana Valley and reported an irrigation water saving of 21% by using SF. It is easy and low-cost, but in the rural area of Uzbekistan, it is difficult to purchase supply pipe and switching valves that are used in SF. Even if it could be procured, there would be a cost burden for *Fermer*.

For this study, in order to enable the adoption of water-saving technology by *Fermer*, we focused on the improvement of furrow irrigation without requiring new facilities and a large increase in labor. To facilitate its smooth introduction, we have simplified the SF by devising a method to reduce the SF from four water supply times to two, with one day interval (simplified SF). Simplified SF was applied to the *Fermer* field in Uzbekistan, and the water-saving effect by simplified SF was analyzed from the measured infiltration on furrows and water advance and recession times.

1.2. Irrigation agriculture and salt accumulation in Uzbekistan

Uzbekistan was forcibly assigned the role of cotton cultivation on farmland from the 1960's during the Soviet Union era where large-scale irrigation development has developed. Consequently, cotton is widely cultivated on irrigated farmland in Uzbekistan. After independence from the Soviet Union in 1991, the intensive cultivation of cotton continued and wheat cultivation for food self-sufficiency expanded. Currently, 100% of cotton and 50% of wheat is purchased by the government under strict production quotas. In general, in *Fermer* farmland, a two-year cultivation cycle is practiced. Cotton is grown from April to September, and wheat is grown from October to June in the same section after cotton cultivation. After wheat cultivation, leaching occurs in December then cotton is cultivated again in the next April. In cotton cultivation, irrigation is necessary due to low precipitation. However, irrigation water cannot reach the lower areas that are far from the main canal, and therefore some farmlands are not cultivated.

In Uzbekistan, 4,281 thousand ha of farmland are equipped with irrigation facilities, and in most of them (4,276 thousand ha), surface irrigation is used. Furthermore, of the 3,700 thousand ha of cultivated irrigated farmland, 1,406 thousand ha of cotton and 1,295 thousand ha of wheat are cultivated under government control (approximately 73%) (Karen, 2013). In cotton and wheat cultivation, furrow irrigation is widely used. However, its downward infiltration loss is large, and the percentage of water stored in the soil layer (effective soil layer) that is consumed by crops from the water reaching the field (application efficiency) is small (approximately 70% compared to 80 - 90% of the sprinkler irrigation) (Maruyama et al., 1998). In addition, the irrigation water that infiltrates downward recharges the groundwater and causes the groundwater level to rise.

Many *Fermer*s lack funds and labor, so that cannot invest in irrigation facilities and irrigation management. They have therefore developed inefficient irrigation management, often resulting in over-irrigation under furrow irrigation which lowers application efficiency. As a result, the groundwater level in the irrigated farmland rises, waterlogging becomes normal, and salt accumulation progresses.

Salt accumulation (the percentage of salinized area (EC_e> 2.0 dSm^{-1})) is large in the six regions of Karakalpakistan, Bukhara, Jizzakh, Navoiy, Syrdarya, and Khorazm, where irrigation is practiced using the Amu Darya and Syr Darya Rivers (hereinafter "Amu River, Syr River") as the water sources. It is thought that excessive irrigation under furrow irrigation is one factor. In particular, the damage to crop production in the Karakalpakistan which is located in the lower basin of the Amu River and faced the Aral Sea, is serious. Salinization is also progressing in the Syrdarya Region located in the middle portion of the Syr River, and salinization occurs in about 98% of the irrigated farmland (**Fig. 2**).

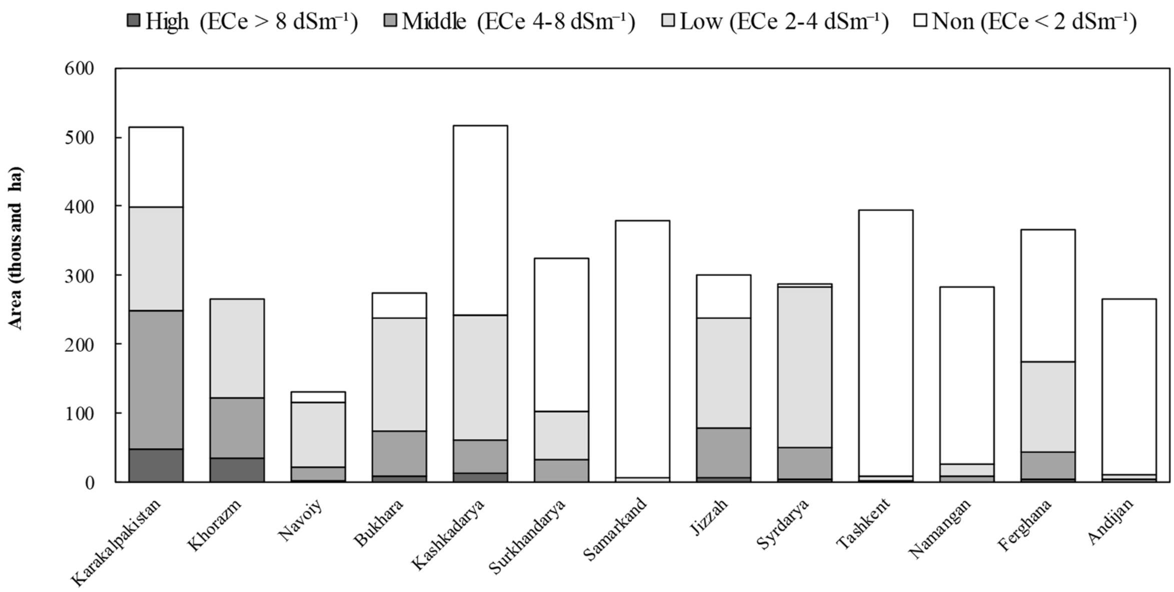


Fig. 2 Salt affected area of each region (2011)

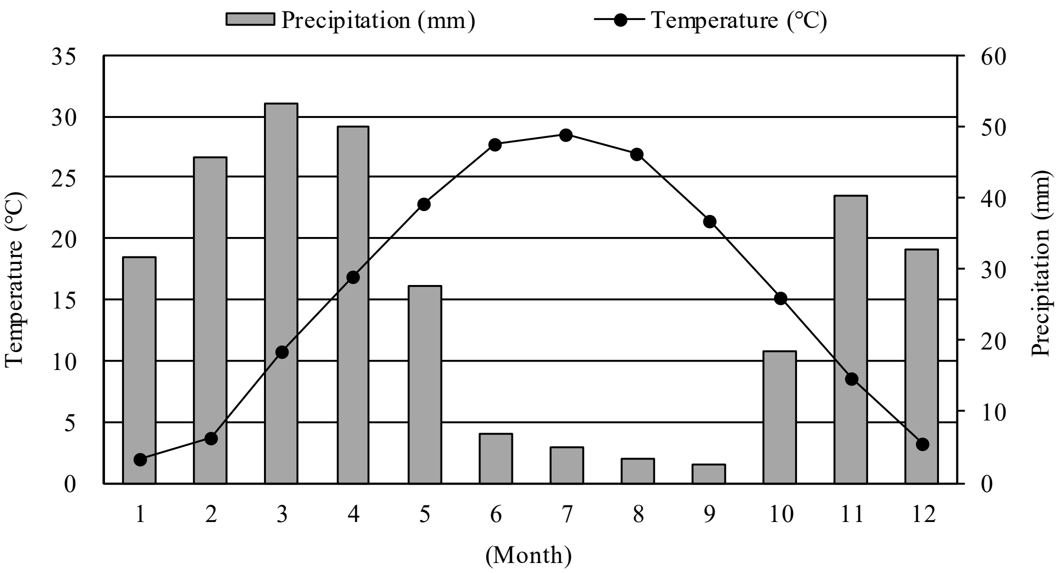
Adapted from data provided by the Farmers' Council of Uzbekistan

As measures against secondary salinization, the introduction of water saving methods such as sprinkler and drip irrigation with less lower infiltration loss is effective, but it requires expensive water supply facilities and maintenance costs, so is difficult for *Fermer*s to introduce.

2. Experimental area

In this research, the Syrdarya Region (**Fig. 3**) was selected as the study area. Approximately 98% of the irrigated farmland in the region is salt affected, and the need for counter measures is considered to be high. The field experiment was conducted at the Pakhtakor field (hereinafter "P field") of *Fermer*, which belongs to the Bobur Water Consumers Association, Oqoltin District. It is located in the southwestern area of the region and operates irrigated agriculture, with the Syr River as its water source. The daily mean temperature of the Syrdarya Region rises to 30 °C in summer and falls to approximately 0 °C in winter. The annual precipitation is approximately 320 mm, but the accumulated precipitation from June to September is very low, being approximately 20 mm (**Fig. 4**).

Fig. 3 Location of Syrdarya Region and Bobur Water Consumer's Association



Source: Yangiyer weather station in Syrdarya region

Fig. 4 Average precipitation and temperature in Syrdarya Region (2004-2015)

In the Oqoltin area, 99% of irrigated farmland is salt affected, but the degree is low. Approximately 74% of irrigated farmland is classified as low level (**Table 2**). The area of the P farm is as large as 136 ha, with a vertically long partition shape of approximately 620 m east-west and 2,200 m north-south. The irrigation canal is located on the eastern side of the farmland, and drainage is located on the western side. In cotton and wheat cultivation, a ridge was constructed from south to north, and a temporary channel was constructed from west to east with a 100–200 m interval. Furrow irrigation was conducted via a temporary channel from south to north.

Table 2 Salt affected area in the Oqoltin district (2008)

Irrigated area	Non (ECe < 2 dSm^{-1})		Low (ECe 2 - 4 dSm^{-1})		Middle (ECe 4 - 8 dSm^{-1})		High (ECe > 8 dSm^{-1})	
ha	ha	%	ha	%	ha	%	ha	%
43,692	551	1.3	32,495	74.4	9,412	21.5	1,234	3.8

A particle size analysis of soil in P field (**Table 3**) was conducted at the Glistan University located in the Syrdarya Region. The particle size ratio of 0.05-0.01 mm was the highest, accounting for 38.6%, 0.05 mm or more accounted for 23.3% and 38.1% accounted for 0.01 mm or less. **Fig. 5** indicates the average value of bulk density ρ_d (100 cm depth) measured at three points in the P field. The bulk density of the surface soil layer was approximately 1.4 g cm^{-3}, however it was high, being from 10 cm to 50 cm deep, and the bulk density was approximately 1.6 g cm^{-3}. It is consequently considered that a hard soil layer was formulated by the long-term compaction of agricultural machinery.

Table 3 Particle size composition (weight fraction)

Weight Fraction (%)						
> 0,25 (mm)	0,25 - 0,1 (mm)	0,1 - 0,05 (mm)	0,05 - 0,01 (mm)	0,01 - 0,005 (mm)	0,005 - 0,001 (mm)	< 0,001 (mm)
2.2	0.4	20.7	38.6	13.6	13.5	11.2

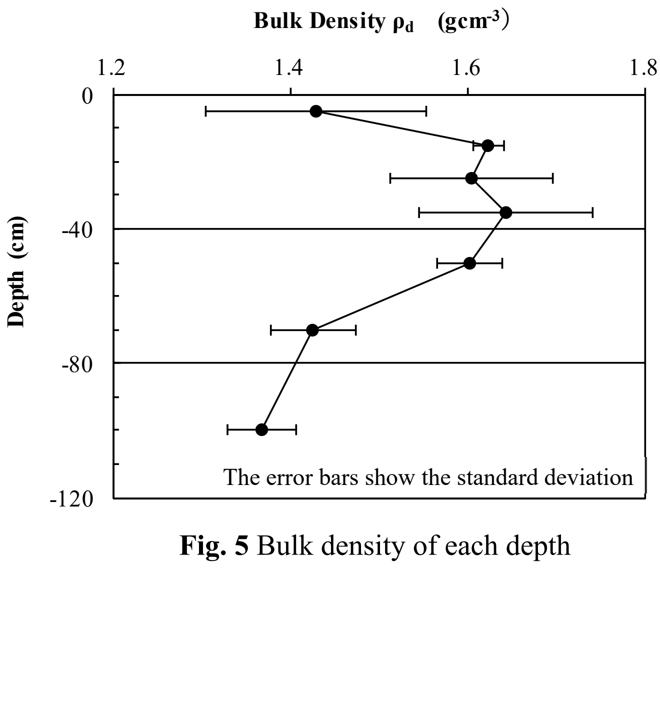


Fig. 5 Bulk density of each depth

3. Materials and Methods

3.1 Condition of experimental field

In the P field, laser leveling was conducted in 2009, cotton was cultivated in April–September 2010, and wheat was cultivated in October 2010–June 2011. The test was conducted during the non-cultivation period after the wheat harvest. The test area was plowed after wheat harvest in July 2011, and then test furrows were created by a tractor in a north-south direction. The interval between ridge and furrow was 0.5 m and 0.4 m which is the most common size for cotton cultivation in Uzbekistan. The average slope of the furrows was approximately 1/800.

3.2 Water flow test

Water was supplied by normal furrow irrigation (conventional) and simplified SF to the test furrow, and then the speed of water advance and water recession time were measured.

In the ordinary SF method, water supply pipe was installed to the water inlet side and water supply was controlled by a start or stop switching valve. Generally, water was supplied intermittently four times following the SF method (**Fig. 6**) (Guy, 2013). If switching work was conducted manually by *Fermer*, it was assumed that the amount of work would increase. However, in simplified SF, water supply pipe is not required nor a lot of additional work by *Fermer*. It simply divides the water application into two phases at one day intervals.

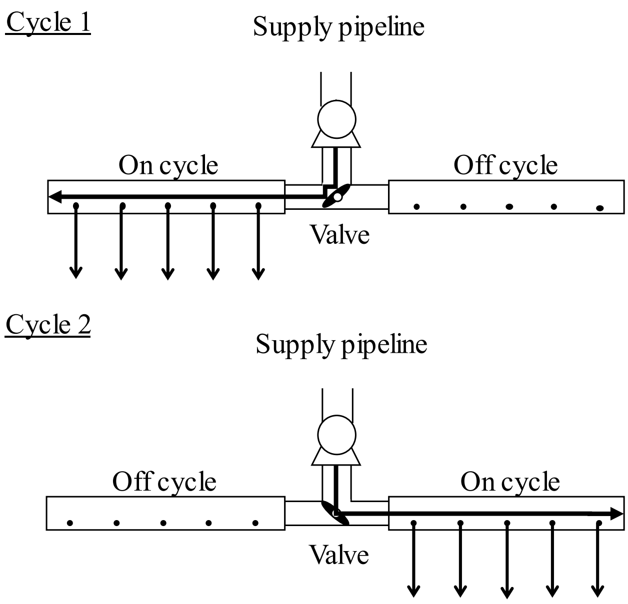


Fig. 6 Typical Surge Flow system

Illustration adapted from Guy F (2013) “Growers Guide to Surge Flow Irrigation”, **Fig. 2**.

In the simplified SF trial for 100 m furrows, water was supplied from the start of the furrow (0 m) for half of the furrow length (0 to 50 m) at first irrigation (SF-1) and when irrigation water reached 50 m of the furrow, the water supply was stopped. When the water supplied by SF-1 disappeared from the surface of furrow (next day of SF-1), the start to the end of the furrow (0 to 100 m) was watered by a second irrigation (SF-2) (**Fig. 7**).

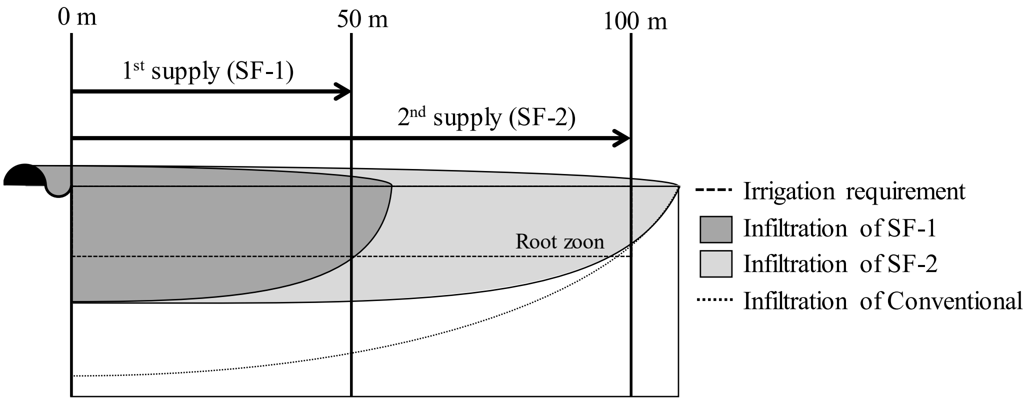


Fig. 7 Method of simplified Surge Flow irrigation

In the water flow test, water was supplied to five furrows with lengths of 100 m by conventional and simplified SF. Water was supplied from a temporary channel, as in *Fermer's* method and inflow rate was controlled at approximately 0.00045 m^3 sec^{-1}.

In simplified SF, the SF-2 was conducted for approximately 20 hours after the SF-1, and when irrigation water reached within 100 m of the furrow, the water supply was stopped. Conventionally, water was supplied until the irrigation water reached 100 m at the end of furrow once, and at that time water supply was stopped. The water was supplied without blocking the 50 m and 100 m points of furrow, and even after stopping the water supply, the water allowed to flow down to over 50 m or 100 m.

3.3 Estimation of furrow infiltration

In order to estimate the infiltration water volume on furrows during the irrigation period, furrow infiltration tests were conducted before the water flow tests. The furrow infiltration test was conducted on dry and wet soil conditions (one day after water supply). The results from the infiltration test in dry soil are assumed to be the values of all dry soil, meaning all the furrow area of conventional and SF-1, and the furrow area of 50-100 m under SF-2. The results from wet soil are assumed to be the values of all wet soil, meaning the furrow area of 0-50 m under SF-2. A Maliot tank supplied the flooding water and the amount of infiltration water was measured 60 minutes after flooding. The Kostiakov's Infiltration Model was used to estimate infiltration:

$$D = ct_i^n \tag{1}$$

where, D is the cumulative infiltration depth at time t_i, t_i is elapsed time (min), c and n are intake constants.

During the water flow test, 'time' was measured at every 10 m of advance in water flow. This was used to estimate water flooding time in the furrow. The furrow flooding time was calculated at each furrow point (1 m interval) during irrigation and time was estimated using the formula (2) proposed by Ikeura et al. (1998):

$$t_a = al^{3} + bl \tag{2}$$

where, t_a is the water advance time until it flows down at the distance l, l is the distance from water inlet (m), a and b are constants.

The recession time of the irrigation water varies, but in this study, it is assumed that it decreases linearly from upstream to downstream, and formula (3) is used:

$$t_r = el + f \tag{3}$$

where, t_r: is the water recession time from water supply at the distance l, l is the distance from water inlet (m) e and f are constants.

From the start and end time of flooding at each point (1 m interval) estimated by the equations (2) and (3), the flood time of irrigation water is calculated. From this time, the infiltration depth (mm) per 1 m was calculated using formula (1). Cumulative infiltration depth at 1 m interval was calculated using formula (4).

$$D = c\left\{\frac{t_r - t_a}{60}\right\}^n \tag{4}$$

The amount of water supplied to the furrows was measured by a triangular weir installed at the inlet.

3.4 Water requirement

In calculating the irrigation water amount, the water supplied beyond the design irrigation requirement is regarded as the loss water, and of the infiltration water at each point, the exceeding infiltration from the Water requirement is regarded as the infiltration loss. Water requirement was determined from the root distribution of cotton and the available moisture (the amount of water effective for crop growth). In root surveys, root samples collected 49 days after sowing in P field were used. The root samples were divided into 5 cm depths, dried at 60°C for 24 hours, and the weight of each layer was measured (**Fig. 8**). The roots were extended to 25 cm depth, but 90.4% of the roots were concentrated at a depth of 10 cm. From this result, the soil layer up to a depth of 10 cm was defined as the critical soil layer on water content for normal growth, which is the soil layer that plays the most dominant role in the water consumption of the effective soil layer.

Available moisture was determined from the results of measurement (pF 1.6-3.2) of the soil of P field imported to Japan by the pressure plate method (DIK-3483, Daiki Rika Kogyo Co. Ltd, Kounosu city, Saitama prefecture, Japan). The soil that was collected at a depth of 0-20 cm was used and was air dried and passed through a 2 mm sieve. The air-dried soil was filled uniformly with 10 cm depth bulk density (ρ_d = 1.47 g cm^{-3}) of P field in a sample cylinder (400 ml, φ= 113 mm, h = 40 mm). After being capillary saturated for 24 hours, it was then used for the test. **Fig. 9** illustrates the relationship between the obtained suction and the soil water content (hereinafter, "pF-water characteristics").

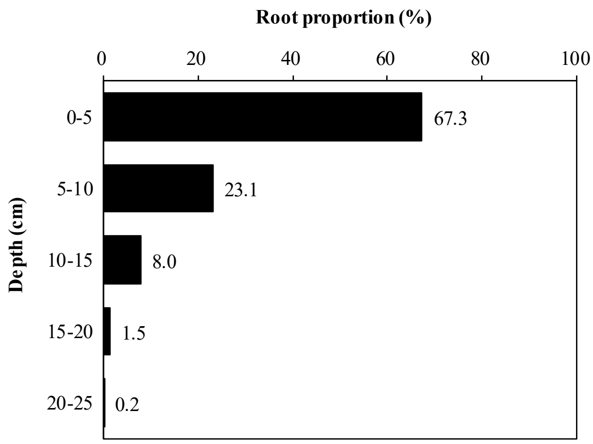


Fig. 8 Root proportion of cotton

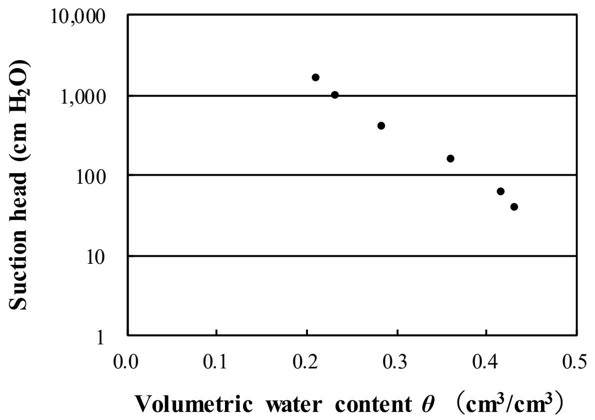


Fig. 9 pF-soil moisture

The available moisture (pF 1.8-3.0) was then set to 0.185 (cm^3 cm^{-3}) (= 0.418-0.233). From the critical soil layer of 0-10 cm and the available moisture of 0.185 (cm^3 cm^{-3}), the total readily available moisture (TRAM) of 20.5 mm was calculated by the equation (5):

$$TRAM = (f_C - M_L) \times D_{ls} \times \frac{1}{C_p} \tag{5}$$

where, f_c is field capacity (m^3 m^{-3}), M_L is depletion of moisture content for normal growth (m^3 m^{-3}), D_{ls} is thickness of critical soil layer (mm), C_p is soil water consumption ratio of critical soil layer. In this study, C_p was substituted by root weight ratio.

In salt-affected farmland, the addition of Leaching Requirement (*LR*) is necessary to control soil salinity. The *LR* (0.032 mm) was calculated using formula (6) (Ayers and Westcot 1994):

$$LR = \frac{ECw}{5ECe - ECw} \tag{6}$$

where, *LR* is the leaching requirement (mm), EC_w is the electrical conductivity of the applied irrigation water in dS m^{-1} (1.2 dS m^{-1}) and EC_e is maximum electrical conductivity to obtain 100% of the cotton yield (7.7 dS m^{-1}).

From *TRAM* and *LR*, Required Water (*RW*, 21.2 mm) was calculated by the formula (7) (Ayers and Westcot 1994):

$$AW = \frac{TRAM}{1 - LR} \tag{7}$$

4. Results and discussion

4.1 Soil texture and saturated hydraulic conductivity of P field

The results of classification into sand, silt and clay by the USDA method based on the particle size analysis of Gulistan University, and the saturated hydraulic conductivity obtained by the falling head permeability test are shown in **Table 4**. From the USDA soil classification, the soil in the P field was classified as Silt Loam. The wide ratio of silt and clay is due to the difference in particle size classification between the Gulistan University and the USDA method.

Table 4 Classification of soil texture and saturated hydraulic conductivity

Location	Classification of soil texture (%)			Saturated hydraulic conductivity (cm s^{-1})
	Sand > 0.02 mm	Silt 0.02 mm - 0.002 mm	Clay 0.002 mm >	
Pakhtakor	23.3	52.1 - 65.6	11.1 - 24.6	1.36×10^{-5}

4.2 Furrow infiltration

Cumulated furrow infiltration before and after water supply obtained from the results of the furrow infiltration test are shown in **Fig. 10** and **Fig. 11**. The value is the average of the results obtained in three tests. **Table 5** indicates the Intake constant and Basic Intake rate (I_b) of the infiltration formula obtained by regression analysis based on the measurement results. The cumulative infiltration of SF-1 and SF-2 showed the same change until about 10 minutes, but after that, the infiltration of SF-2 gradually decreased after 60 minutes. SF-2 decreased by 9.5 mm compared to SF-1. In addition, I_b of SF-2 decreased to less than 50% before water supply (SF-1). The variation in the measurement results was large in SF-1 and small in SF-2. It is considered that the permeability of the furrow can be uniformly reduced by supplying water in advance, even in the furrow with uneven permeability.

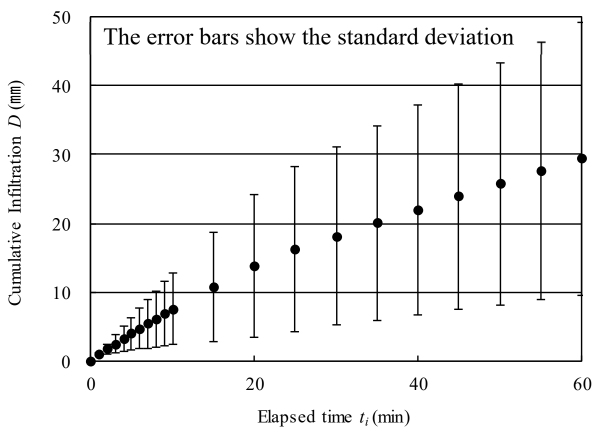


Fig. 10 Cumulative infiltration curve (before water supply)

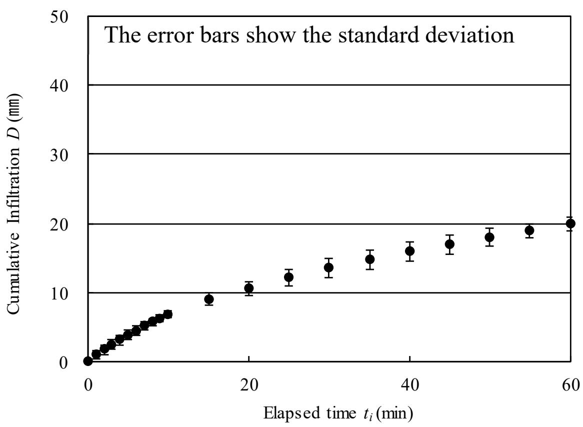


Fig. 11 Cumulative infiltration curve (after water supply)

Table 5 Intake constants c, n, and basic intake rate I_b

Treatment	***c***	***n***	***I_b (mm hr^{-1})***
SF-1	1.059	0.83	24.0
SF-2	1.202	0.71	11.5

4.3. Water advance speed

In each treatment, water was supplied to five furrows with lengths of 100 m. The test plot was conducted using laser leveling with a 1/800 slope in 2009, and flow test was conducted on neighboring furrows to make same condition. The slope of furrow was made by the same tractor, but there was some unevenness. The cessation of water flow occurred in three furrows under the conventional method. Conversely, the simple SF method did not cause water stagnation, and water flow of up to 100 m was completed in all furrows. Therefore, in simplified SF, it could be considered that reduction of permeability and smoothing of furrows by SF-1 made it possible for SF-2 to reach the end of furrows without stop of water. However, even in the simplified SF, there is a possibility that water stoppage due to the unevenness of furrows may occur in SF-1 and the non-flowing section (50-100 m) of SF-2. Although it is difficult to eliminate the unevenness of the furrows completely, measures such as making uniform furrows and increasing inflow (m^3 sec^{-1}) rate are considered necessary.

The distance of water movement and elapsed time under the conventional and the simplified SF are shown in **Fig. 12** and **Fig. 13**. **Table 6** shows the constants of the water advance formula obtained by regression analysis based on the measurements. The three furrows in which the stagnation occurred under the conventional method were excluded from the comparison. The average value of two furrows under conventional and five furrows under Simple SF was used.

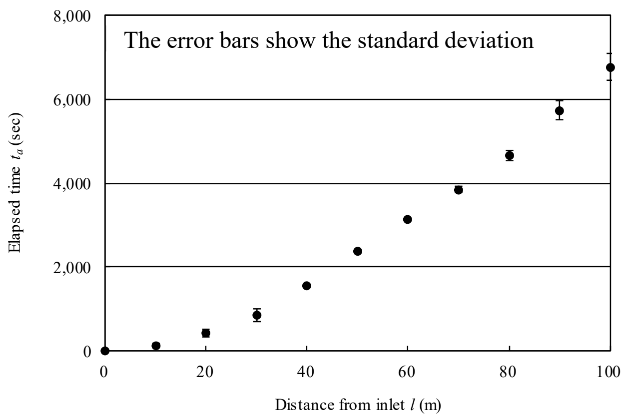


Fig. 12 Water advanced curve (Conventional)

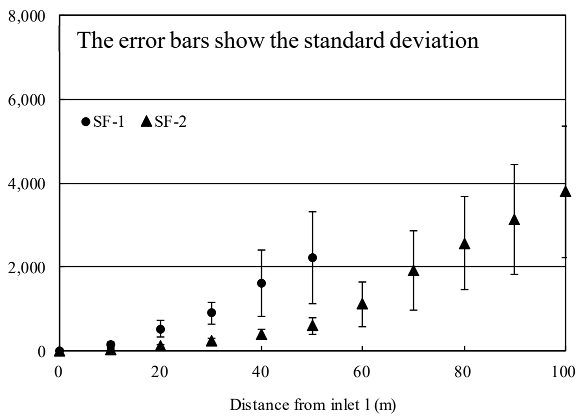


Fig. 13 Water advanced curve (SF-1, SF-2)

Table 6 Water advance constants *a*, *b*

Treatment	***a***	***b***
Conventional, SF-1	0.00326	36.72
SF-2	0.00321	8.21

In conventional, the time required for the irrigation water to reach 50 m and 100 m points of furrows was 2,367 seconds (~39 minutes) and 6,768 seconds (~112 minutes), respectively. In the SF-1 of the simplified SF, the arrival time to the 50 m point was 2,220 seconds (37 minutes), which was close to the conventional. In SF-2, it reached the point of 50 m in 613 seconds (~10 minutes), and the time was shortened by more than 70% compared with the conventional method and SF-1. The arrival time of SF-2 to the 100 m point was 3,806 seconds (~63 minutes), which was approximately 56% shorter than the conventional method. From these results, the time required for the simplified SF method (the sum of SF-1 and SF-2) is 6,026 seconds (~100 minutes), which was shortened by 742 seconds (~12 minutes) compared to the conventional time of 6,768 seconds (~112 minutes). By shortening the water flow time by applying simplified SF, the amount of water supplied to the furrows was reduced by approximately 11%, and the amount of water loss was reduced by approximately 15%. Therefore, in simplified SF, water flow of up to 50 m of furrow by SF-1 causes a uniform decrease in permeability and smoothing of furrows, and as a result, the water advance speed in SF-2 was greatly improved.

However, in the application example of the SF method in Fergana, the water saving effect obtained was approximately 21%, but in this simplified SF, it was approximately 11%. This is considered because the amount of water supply was as low as two (Ferugana case: 4 times), the water supply interval was long (approximately 20 hours), and the water supply ratio was low, at 0.00045 m^3sec^{-1} (Fergana case: 0.0012-0.0030 m^3 sec^{-1}).

4.4 Water recession time

Water recession time of conventional and simplified SF is shown in **Fig. 14** and **Fig. 15**. **Table 7** shows the constants of the water recession formula obtained by regression analysis based on the measurement results. The water recession time is the time from the arrival of irrigation water at each point to the disappearance of the water from the surface of the furrow. The construction level of furrows was similar, but due to local unevenness in the furrows, the irrigation water recession time varied in both conventional and simplified SF.

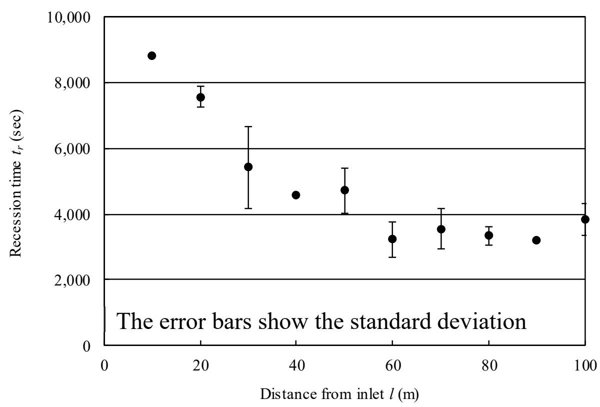


Fig. 14 Water recession time (Conventional)

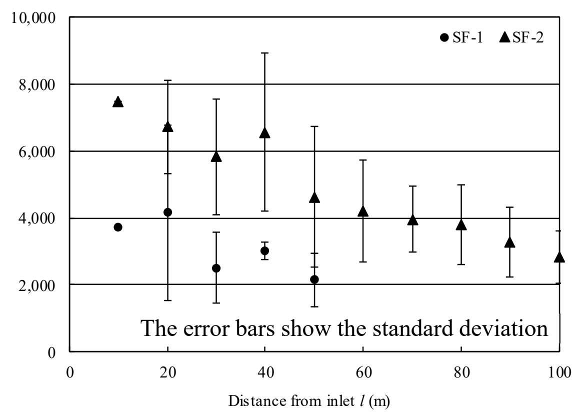


Fig. 15 Water recession time (SF-1, SF-2)

Table 7 Water recession constants *e*, *f*

Treatment	***e***	***f***
Conventional	-54.7	7,834
SF-1	-42.9	4,399
SF-2	-50.9	7,729

In both the conventional, SF-1 and SF-2, the water recession time tended to decrease from the water inlet side to the lower side. Compared with the conventional, water advance speed of SF-2 improved, but there was no large difference in the water recession time.

4.5 Estimation of infiltration water

The estimated amount of infiltration water is shown in the reference level because there is a possibility of underestimating the infiltration loss of the conventional due to there being a large variation in the results of the furrow infiltration test in dry soil. The distribution of infiltration water which was calculated by the formula of infiltration, water advance and water recession is shown in **Fig. 16**. In both the conventional and the simplified SF, the amount of infiltration water decreased from the inlet to the lower section.

The infiltration water of SF-2 decreased by up to 50 m due to the reduction effect of SF-1. Its reduction was 50.9 mm at the inlet, and 32.5 mm at the 50 m point of the furrow compare with conventional. However, the amount of infiltration increased after entering the unirrigated section after 50 m of furrow. **Fig. 17** shows the total amount of infiltration water in the simplified SF that combines SF-1 and SF-2. Conventional and simplified SF, 21.2 mm, which required water volume, was supplied to the entire section of the 100 m furrow.

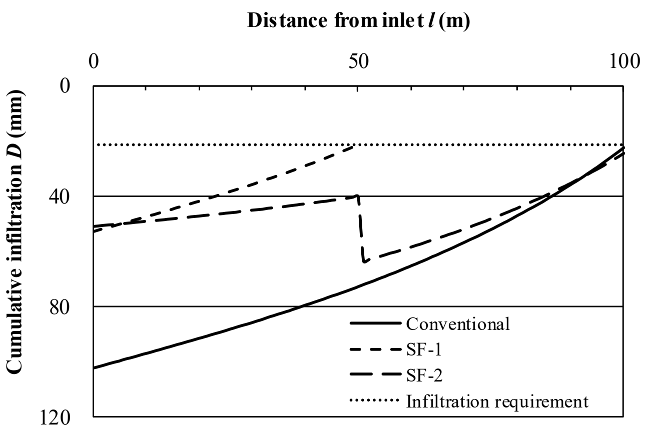


Fig. 16 Distribution of infiltration water of each method

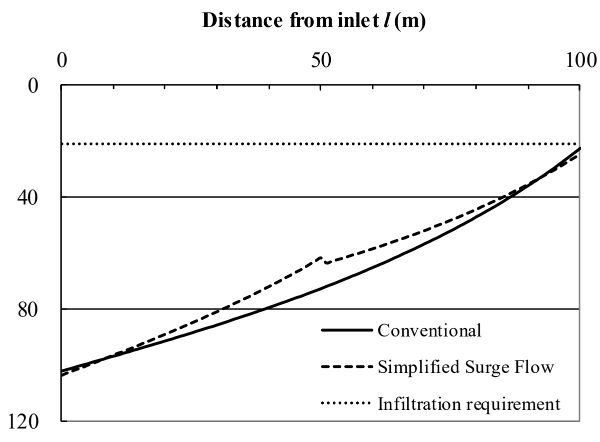


Fig. 17 Distribution of infiltration water of each method

In both conventional and the simplified SF, the amount of infiltration water at end of the furrow (outlet) section is around required water. At the water inlet, the simplified SF supplies water twice with SF-1 and SF-2, so the conventional and the simplified SF have the same amount of infiltration water. However, the amount of infiltrated water at the 50 m point in the center of the furrow decreased by 11.0 mm in the simplified SF compared to the conventional and the amount of infiltrated water in the simplified SF decreased in the 8-92 m section, with the maximum at the 50 m point. Therefore, in the simplified SF, the water-saving effect is considered the highest at the 50 m point, which is the end of the section that passes through SF-1. As the water-saving effect was small compared to the normal SF, it is, however, necessary to study for a larger water-saving effect, such as shortening the furrow length. In the normal SF, water supply and stop were repeated at short intervals, but in the simplified SF of this test, the water supply interval between SF-1 and SF-2 was long (approximately 20 hours). For this reason, the reduction effect of infiltration by the simplified SF as lowered. As an improvement measure, it is considered effective to shorten the water supply interval by implementing SF-1 in the evening and performing SF-2 in the early morning of the following day.

The amount of supplied water to the furrow measured by the triangular weir at the water inlet was 3.03 m^3 by the conventional and 2.70 m^3 by the simplified SF. The reduction of irrigation water was approximately 11% and the reduction of infiltration loss was approximately 15%. Conversely, the infiltration water volume was 2.77 m^3 by the conventional and 2.62 m^3 by the simplified SF. Infiltration water volume was reduced by approximately 5% and the infiltration loss was reduced by approximately 8%. The reason why the reduction of infiltration water was smaller than the supplied water may be that flooding time in the 100 m furrow was decreased due to runoff caused by the unblocked end of the furrow (outlet). Therefore, we conclude that the amount of infiltration water can be further reduced by closing the end of the furrow and stopping the water supply earlier.

5. Conclusion

In this study, we examined the water-saving effect using the simplified SF with improved furrow irrigation, with the consideration that it is easy to be adopted by *Fermer*. In the normal SF, water supply pipe is installed on the upstream side of the field, and the water saving effect is obtained by intermittent water supply with a switching valve (Walker, 1989). However, even with the simplified SF, which does not have a water supply pipe or valve and just divide regular furrow irrigation to twice with one day interval, it can reduce the amount of supplied water by approximately 11% and infiltration loss by approximately 15%. This is achieved by decreasing permeability and smoothing the furrow surfaces by SF-1. This suggests that the simplified SF can be an effective first step in water conservation because it can be easily applied to the current furrow irrigation even in developing regions that have water management issues. Furthermore, the combination of simplified SF and other water saving technology such as land leveling (Ikeura et al., 2011) and alternate furrow irrigation (AFI) which irrigates every other furrow, is considered possible to further reduce the amount of irrigation water and infiltration loss. In this water flow test, however, irrigation water stagnated due to local unevenness, so in order to obtain a sufficient water-saving effect by the simplified SF, the creation of uniform furrows and increase of inflow rate (m^3 sec^{-1}) is necessary to suppress the effects of uneven furrows.

In this test, priority was given to workability in the vast field of Uzbekistan, and the distance of irrigation furrows at SF-1 was set to 50 m, but the water-saving effect was lower than the normal SF. Ikeura et al. (1998) proposed short furrow lengths for the purpose of optimizing the application efficiency under border irrigation in sandy fields, so that the lengths of irrigated furrow such as shortening SF-1 lengths would maximize water-saving effects. Furthermore, in Uzbekistan, the crushing of the hard soil layer is being conducted for the purpose of improving poor drainage and leaching effects. However, it is possible that the large pore generated by crushing promotes the preferential flow of irrigation water. There is a risk that infiltration loss during irrigation will increase. As a future issue for the field application of the simplified SF, it will be necessary to verify the synergistic effect of the combined use of the simplified SF and AFI, the measures to suppress the influence of unevenness in the furrows, optimal water flow distance, and water-saving effects at drainage improvement fields.

Acknowledgments

This study was compiled through participating in the “The Research Project on Measures against Farmland Damage from Salinization”, an overseas agricultural and rural environmental survey, which is a subsidy project of the Ministry of Agriculture, Forestry and Fisheries in Japan. For the field survey and research in Uzbekistan, we are deeply appreciative of the cooperation and advice from the Ministry of Agriculture and Water Resources, Farmers' Council of Uzbekistan, Institute of Irrigation and Water Problem, and Bobur Water Consumers Association.

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Suitable inflow rate and furrow length for Simplified Surge Flow Irrigation

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Summary

In the arid lands covering Uzbekistan, furrow irrigation with low application efficiency is still widely used due to a lack of funds and shortage of labor. To save water and prevent secondary salinization caused by excessive irrigation, it is important to adopt low-cost and easy water-saving irrigation methods. Onishi et al. (2017) proposed simplified Surge Flow (SF) irrigation that does not require expensive equipment and merely divides the water supply into two phases at one-day intervals. This study conducted the suitable inflow rate and furrow length of simplified SF to improve water application efficiency in Uzbekistan. Five experimental plots (total area of 2,250 m^2, with 25 furrows) were set up and the inflow rates for two plots were 5 Ls^{-1} (F5.0) and that for the others were 1.7 Ls^{-1} (F1.7). The conventional irrigation method (F5.0C and F1.7C) and simplified SF (F5.0S and F1.7S) were applied to cases of furrow length of 100 m under each inflow rate. In addition, simplified SF was applied on a 50 m furrow at F1.7 (F1.7S-50). In the first irrigation using simplified SF, water was supplied from the start point of the furrow (0 m) for half of the furrow length (50 m, 25 m). In the second irrigation, water was supplied from the start point to the end of the furrow (100 m, 50 m). The application efficiency in F1.7S and F1.7S-50 was higher than that in F1.7C and F1.7C-50, and the highest was in F1.7S-50. The water supply duration was shorter in F5.0S, but the total volume of supplied water was larger than that of F1.7C. These results indicate that shortening furrow length might be an effective way to save water using simplified SF with a low inflow rate, and in contrast, that it is necessary to extend furrow length with a high inflow rate.

Keywords

Arid land, Salinization, Water-saving, Furrow irrigation, Surge Flow irrigation

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1. Introduction

1.1 Back ground

Irrigated agriculture has the potential to increase crop yields and make a significant contribution to food security. The FAO estimates that irrigated farmland produces 40% of the world's crops while occupying only 20% (300 million ha) of global cultivated area (1.6 billion ha) (FAO, 2011). On the contrary, soil salinity is a major abiotic stress, and reduces global agricultural productivity. Salinization of arable land has dramatically increased in the last few decades (Martin et al., 2012), and it has had a global impact; one forecast shows 30% of arable land will be lost by around 2028, and up to 50% by 2050 (Wang et al., 2003). In addition, 1-2% of global irrigated area is lost to salinization every year, with its effect in arid and semi-arid regions being particularly large (FAO, 2002). In arid and semi-arid regions, irrigation is indispensable for agricultural production, but inappropriate water management causes secondary salinization. There are two main causes of secondary salinization: the inflow of salts within irrigation water, and the rise in groundwater table due to poor drainage. If salts do not leach out of soil, they accumulate through evaporative water loss and root water uptake (Devkota et al., 2015). In general, water-saving and drainage improvement techniques are carried out to mitigate salinization. Salt leaching is, because of its low cost, also a popular salinity removal measure among farmers.

1.2 Salinization in Central Asia

In Central Asia, which is an arid and semi-arid region, there has been remarkable secondary salinization caused by inappropriate water management. Large-scale irrigation was conducted from the 1960s (during Soviet Union era) in the Amu-Darya and Syr-Darya river basins, which were previously steppe or desert areas. In the Republic of Uzbekistan (hereafter, “Uzbekistan”), cotton production with furrow irrigation was carried out on much of the irrigated farmland. Although irrigation greatly increased the agricultural production of the former Soviet Union, inappropriate water management caused severe salinization. As a result, Uzbekistan has the largest area of salt-affected farmlands among the Central Asian countries (**Table 1**) (Karen, 2013). Salt-affected farmland is defined as farmland where the electrical conductivity of the saturated extract of soil (EC_e) is 2 dS m^{-1} or more. Furthermore, soils from the plains of Central Asia are naturally rich in salt. In addition, the development of irrigation has increased the risk of secondary salinization (Shirokova and Morozov, 2006).

Table 1 Salinized area of the total area under irrigation in Central Asia

Country	Area equipped for irrigation		Area salinized by irrigation		
	Year	ha	Year	ha	(%)
Uzbekistan	2005	4,198,000	1994	2,141,000	51
Kyrgyz	2005	1,021,400	2005	49,503	5
Tajikistan	2009	742,051	2009	23,235	3
Kazakhstan	2010	2,065,900	2010	404,300	20
Turkmenistan	2006	1,990,800	2002	1,353,744	68
Total		10,018,151		3,971,782	40

Source: Irrigation in Central Asia in figures (Karen, 2013, FAO Water Reports 39, pp 68)

1.3 Irrigated agriculture in Uzbekistan

In Uzbekistan, even after 27 years of independence from the Soviet Union, the government continues to control cotton and wheat production. Current cotton and wheat production are carried out by the agricultural corporation "*Fermer*," which has long-term lease agreements to use government farmland (Onishi, 2017). Of the 3,700 thousand ha of total irrigated farmland harvested in Uzbekistan, cotton accounts for 1,406 thousand ha, and wheat accounts for 1,295 thousand ha (Karen, 2013). 73% of harvested farmland by irrigation is under government control. The area of farmland managed by *Fermer* is vast (around 50 ha or more), and the corporation widely practices furrow irrigation. In Uzbekistan, surface irrigation is conducted on 4,276 thousand ha (in 1994), which is 92% of the cultivated area (4,651 thousand ha, in 2009) (Karen, 2013). The advantages of surface irrigation are its simplicity of use by farmers, low capital investment requirement, and resistance to wind (Walker, 1989). Contrarily, its disadvantages are its low application efficiency and high labor requirement (Walker, 1989). 90% of global irrigated land is irrigated using relatively inefficient surface irrigation methods (Siyal et al., 2016). In the case of furrow irrigation, it is necessary to dig channels to introduce water, and salts tend to accumulate in the top of ridge where crop is planted (Brouwer, 1985). *Fermer* cannot make investments to improve the infrastructure for water management in most cases, owing to a lack of funds and labor force. Consequently, careless irrigation has been conducted, and excessive irrigation is often observed on *Fermer* farmlands. Excessive irrigation has caused large amounts of salts to be deposited onto farmlands, raising the groundwater table and causing secondary salinization. Therefore, water conservation at the time of irrigation is important to prevent salinization. However, it is still difficult for *Fermer* to install highly efficient irrigation systems, like drip or sprinkler systems, because of a lack of funds.

1.4 Water-saving based on furrow irrigation (simplified Surge Flow irrigation)

Surge Flow irrigation (SF) is a water conservation method based on furrow irrigation (**Fig. 1**). The SF method achieves water conservation by irrigating intermittently instead of continuously.

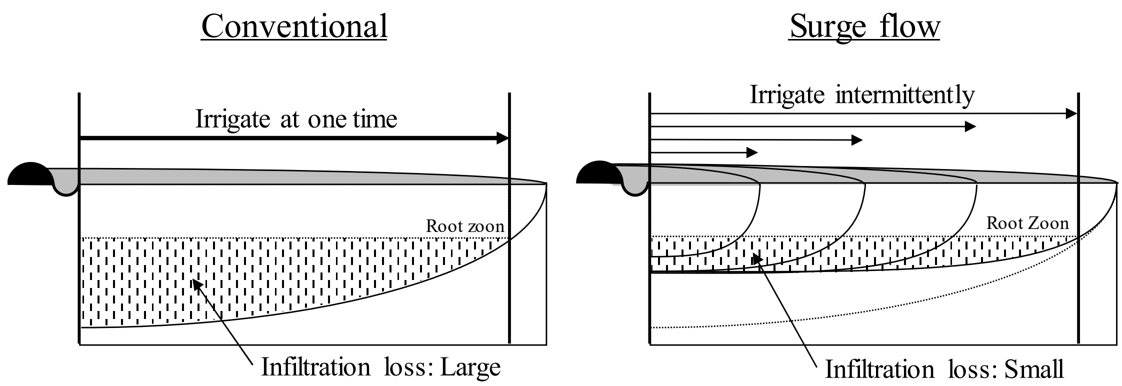


Fig. 1 Concept of Surge Flow irrigation

The advantage of SF is that it decreases infiltration loss by reducing soil permeability through cyclic irrigation. The first water supply reduces soil permeability, speeding up water flow during the second water supply. Four physical processes cause the reduction in infiltration: consolidation, owing to soil particle migration and reorientation; air entrapment; the redistribution of water; and channel smoothing (Alan and Karen, 1994). Alan and Karen (1994) reported that SF has resulted in an approximately 50% saving of irrigation water without significant reduction in peppermint yield, from the level consumed by conventional irrigation. In Uzbekistan, Horst et al. (2005) conducted an experiment at a cotton field in Central Fergana Valley and reported an irrigation water saving of 21% by using SF.

SF is a useful method to save water, but it requires irrigation equipment such as supply pipes and switching valves; therefore, introduction of the method might be difficult for *Fermer*. Considering the physical and economic state of *Fermer*, Onishi et al. (2017) proposed the 'simplified SF' method (**Fig. 2**), which does not require expensive equipment. The method simply divides water application into two phases at one-day intervals (SF-1 and SF-2). They found that the method saved around 10% of water. In this study, optimum inflow rates and furrow lengths of simplified SF were conducted to improve water application efficiency.

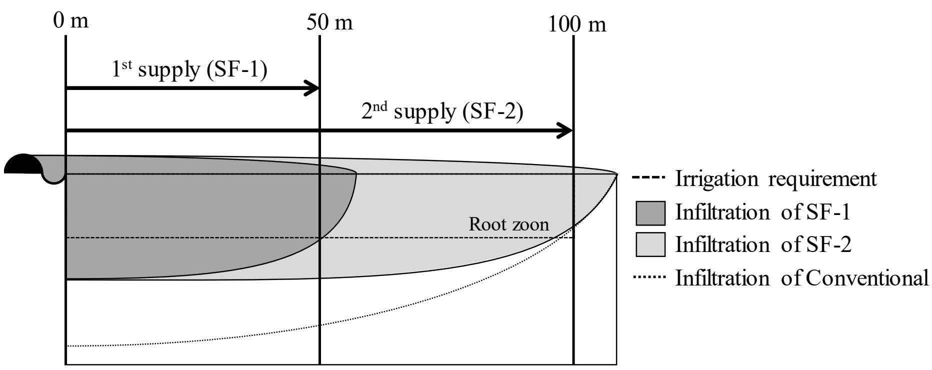


Fig. 2 Concept of simplified SF

2. Materials and Methods

2.1 Study Area

The field study was conducted at the Nozima Durdona Fayz farm (N farm), which belongs to the Axmedov Water Consumer's Association in the Mirzaabad district of the Syrdarya Region (**Fig. 3**). In the Syrdarya Region, 98% of the irrigated farmlands is salt-affected (Onishi et al., 2017), average daily temperature reaches 30°C in summer and drops to 0°C in winter. Total annual precipitation in the region is 320 mm, however, the cumulative precipitation from June to September is very low (20 mm).

The size of a typical field in Syrdarya Region is approximately 40-60 ha and that of the N farm is approximately 51 ha (820 m×620 m). In the N farm, irrigation canal is located on the east of the farmland, whereas the drainage is located on the north and west of the farmland. Usually, irrigation is conducted two or three during cotton cultivation. The irrigation water is supplied to plots divided by temporary channels. The typical size of a plot is about 5-10 ha and the furrow length are approximately 200 m. We measured the inflow rate to one furrow, and it ranged between 0.5 and 2.0 Ls^{-1}.

The properties of N farm soil were analyzed using soil samples from depths of 5, 15, 25, 35, 50, and 70 cm. Bulk density, saturated hydraulic conductivity, and soil texture are shown in **Table 2**.

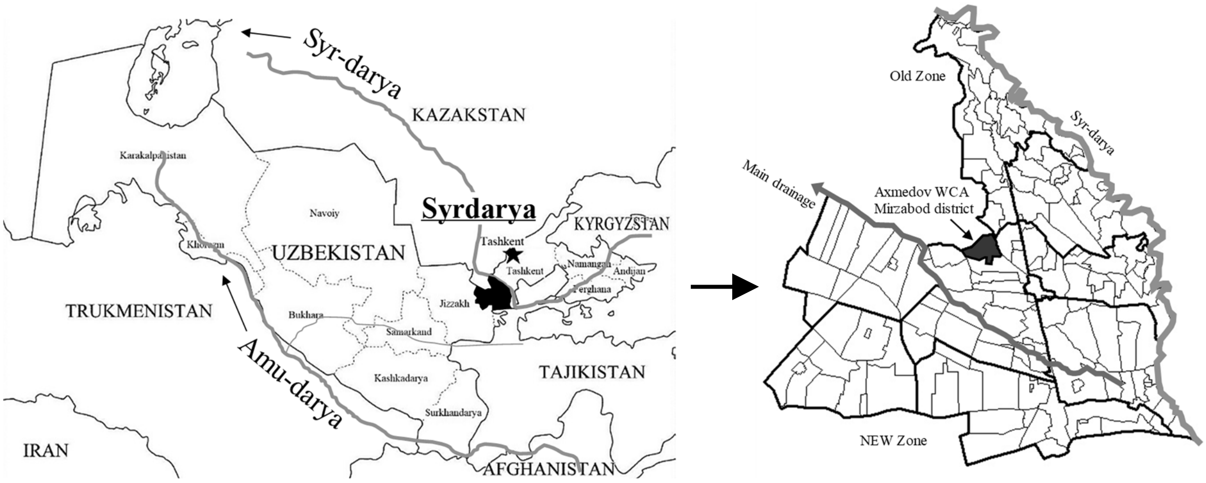


Fig. 3 Locations of Syrdarya Region and Axmedov Water Consumer's Association

Table 2 Physical properties of N farm soil

Depth (cm)	Bulk density (g cm^{-3})	Saturated hydraulic conductivity (cm s^{-1})	Texture			Soil type
			Clay (%)	Silt (%)	Sand (%)	
5	1.37	3.07×10^{-4}	12.8	32.8	54.4	Loam
15	1.40	6.03×10^{-4}	13.2	31.2	55.6	Loam
25	1.56	4.06×10^{-5}	16.8	29.0	54.2	Clay Loam
35	1.62	4.62×10^{-5}	14.1	31.8	54.2	Loam
50	1.49	2.26×10^{-4}	15.6	29.0	55.3	Clay Loam
70	1.46	4.03×10^{-4}	9.3	35.2	55.5	Loam

Bulk density of surface soil (to a depth of 15 cm) is 1.4 g cm^{-3} but at depths of 25 cm to 35 cm it is 1.6 g cm^{-3}; here is it assumed that a hard soil layer has formed. Saturated hydraulic conductivity is lower in the hard soil layer (25-35 cm depth) than it is in the other layers. All depths were classed as either loam or clay loam according to the standards of the International Society of Soil Science. Readily Available Water (RAW: pF 1.8-3.0) was obtained from the soil moisture characteristic, which was analyzed using the pressure plate method (DIK-3483, Daiki Rika Kogyo Co. Ltd, Kounosu city, Saitama prefecture, Japan). Soil moisture characteristics are shown in **Table 3**.

Table 3 Soil moisture characteristics (cm^3 cm^{-3})

Depth (cm)	Field capacity (pF 1.8)	Depletion of moisture content for normal growth (pF 3.0)	Primary wilting point (pF 3.8)	Readily available water (RAW) (pF 1.8-3.0)
5	0.353	0.202	0.180	0.151
15	0.349	0.206	0.187	0.143
25	0.352	0.245	0.220	0.106
35	0.340	0.246	0.221	0.094
50	0.365	0.198	0.174	0.167
70	0.388	0.174	0.144	0.214

Field capacity (pF 1.8) was between 0.340 and 0.388 cm^3 cm^{-3}, Depletion of moisture content for normal growth (pF 3.0) was between 0.174 and 0.246 cm^3 cm^{-3}. The RAW of the hard soil layer (25-35 cm depth) was lower than it was in other layers.

2.2 Experimental setup and treatment

The experiment was conducted during the cotton cultivation period on the northeastern side of the N farm in July 2017. The average field slope is 1/1000. Furrows and ridges were made using a tractor and their widths were 0.4 m and 0.5 m respectively. Irrigation water was supplied using a gasoline pump (LGP 20-A, Leo Group Co., Ltd., Wenling city, China, discharge rate: 5 Ls^{-1}). The electrical conductivity of irrigation water was 1.42 dS m^{-1}. Five plots (total area of 2,250 m^2, with 25 furrows) were set up for the experiment (**Fig. 4**). Although normal inflow rate is 0.5 to 2.0 Ls^{-1}, advance of the water was often stopped due to unevenness of furrow. Therefore, in this study, a high flow rate more than twice the normal rate was applied to avoid the effects of the unevenness of the furrows. Further, it can be expected that infiltration loss decreases with the shortening in the irrigation time under high flow rate. In two plots, irrigation water was supplied to each furrow at an inflow rate of 5 Ls^{-1} per furrow (F5.0). In the other three plots, irrigation water was supplied to each furrow at an inflow rate of 1.7 Ls^{-1} per furrow (F1.7).

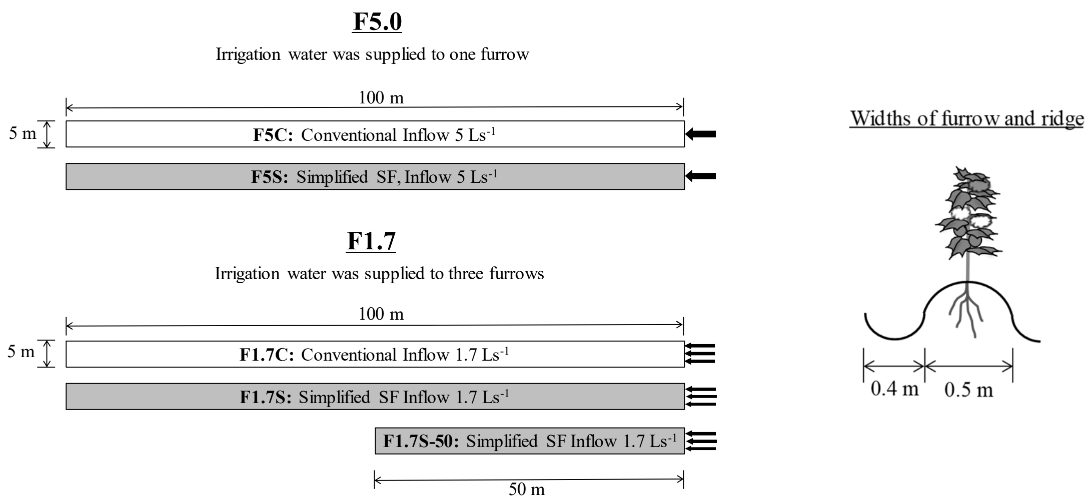


Fig. 4 Design of experimental plots

In each plot, a conventional and simplified SF method was applied to 100 m (F5.0C, F5.0S, F1.7C and F1.7S); and in addition, simplified SF was applied on a 50 m furrow in plot F1.7 (F1.7S-50). The ends of all the furrows were blocked and when irrigation water reached the end of the furrow, the water supply was stopped. In the simplified SF trial, water was supplied from the start of the furrow (0 m) for half of the furrow length (50 m, 25 m) at first irrigation (SF-1), and from the start to the end of the furrow (100 m, 50 m) at second irrigation (SF-2). The SF-2 was conducted about 20 hours after the SF-1. This water flow test had three replicates comprising the central three furrows of each plot (the two furrows at both ends of the five furrows in the plots were not used).

2.3 Estimation of furrow infiltration

In order to estimate the amount of infiltration water during the irrigation periods, furrow infiltration tests were conducted before the water flow tests. The furrow infiltration test was carried out on dry soil and wet soil (one day after water supply) conditions, a Maliot tank supplied the flooding water and the amount of infiltration water was measured 60 minutes after flooding. The results from the infiltration test in dry soil are assumed to be the values of all dry soil, i.e. all the furrow area of conventional and SF-1, and the furrow area of 25-50 m or 50-100 m under SF-2. The results from wet soil are assumed to be the values of all wet soil i.e. the furrow area of 0-25 or 0-50 m under SF-2. Kostiakov's Infiltration Model was used to estimate infiltration.

$$D = ct_i^n \tag{1}$$

where, D is the cumulative infiltration depth at time t_i, t_i is elapsed time (min), c and n are intake constants. The Basic Intake rate Ib of each condition was calculated using formula (2).

$$I_b = 60cn\{600(1-n)\}^{n-1} \tag{2}$$

During the water flow test, 'time' was measured at every 10 m advance in water flow; this was used to estimate water flooding time in the furrow. The furrow flooding time was calculated at each furrow point (1 m interval) during irrigation; time was estimated using the formula (3) proposed by Ikeura et al. (1998).

$$t_a = al^3 + bl \tag{3}$$

where, t_a is the water advance time until it flows down at the distance l, l is the distance from water inlet (m), and a and b are constants. In this study, cumulative infiltration depth at 1 m interval was calculated using formula (4).

$$D = c\left\{\frac{t_f - t_a}{60}\right\}^n \tag{4}$$

where, t_f is the finishing time of water supply.

The estimation of infiltration water focused on the irrigation period

2.4 Water requirement

Water requirement (mm) was determined from the soil moisture consumption and RAW. Soil moisture consumption was determined by using the volumetric water content of sampling soil which was sampled twice: 24 hours and 12 days after irrigation. Soil sampling was conducted on the 14th and 25th of July 2017, and during this term there was no rain. According to groundwater monitoring data from the experimental field in July 2015, the groundwater table fell to approximately -2.5 m by the time of irrigation, and then it was raised to approximately -1.5 m after irrigation. After the irrigation term, the groundwater table fell gradually, and then stabilized at approximately -3.0 m until the leaching term in December.

Soil moisture was reduced to a depth of 30 cm from 24 hours to 12 days after irrigation, about 58% of which was reduced at the surface soil layer (up to 10 cm depth). Therefore, the effective soil layer is up to 30 cm deep and the critical soil layer for water content for normal growth was concluded to be the surface layer (10 cm). From the *RAW* of the surface soil layer (0.151 m^3 m^{-3}) and thickness of critical soil layer (10 cm), Total Readily Available Moisture (*TRAM*, 26.1 mm) was obtained using formula (5).

$$TRAM = (f_c - M_L) \times D_{ls} \times \frac{1}{C_p} \quad (5)$$

where, f_c is field capacity (m^3 m^{-3}), M_L is depletion of moisture content for normal growth (m^3 m^{-3}), D_{ls} is thickness of critical soil layer (mm), C_p is soil water consumption ratio of critical soil layer. In salt-affected farmland, it is necessary to add Leaching Requirement (*LR*) to control soil salinity. The *LR* (0.038 mm) was calculated formula (6) (Ayers and Westcot, 1994).

$$LR = \frac{EC_w}{5EC_e - EC_w} \quad (6)$$

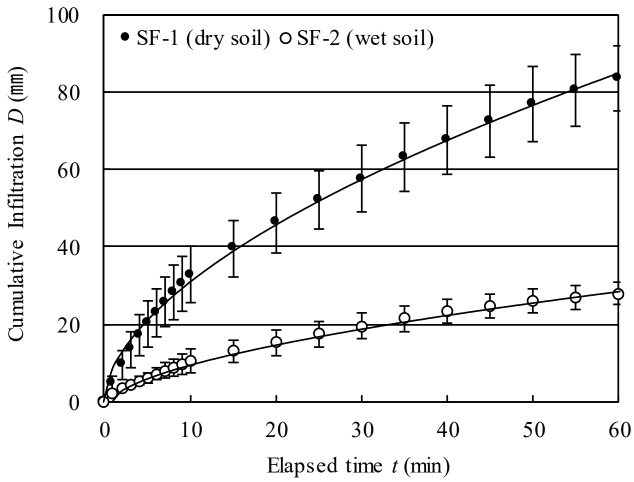
where *LR* is the leaching requirement (mm), EC_w is the electrical conductivity of the applied irrigation water in dSm^{-1} (1.42 dS m^{-1}) and EC_e is maximum electrical conductivity to obtain 100% of the cotton yield (7.7 dS m^{-1}). From *TRAM* and *LR*, Required Water (*RW*, 27.2 mm) was calculated by the formula (7) (Ayers and Westcot, 1994).

$$RW = \frac{TRAM}{1 - LR} \quad (7)$$

3. Results and Discussion

3.1 Furrow infiltration

The cumulative infiltration data as functions of time under dry (SF-1) and wet (SF-2) condition are shown in **Fig. 5**. Dots are the average of three trials in the field. Basic intake rate (I_b) and intake constants obtained by regression analysis are listed in **Table 4**. The amount of cumulative infiltration after 60 minutes of SF-1 and SF-2 were 83 mm and 28 mm, respectively. Variation of data for SF-2 was smaller than that of SF-1. The basic intake rate of SF-2 was 63% lower than that of SF-1. A large reduction in I_b was also reported by Onishi et al. (2017) for a different land area managed by the Water Consumer's Association.



*The error bars show the standard deviation

Fig. 5 Cumulative infiltration curve

Table 4 Basic intake rate I_b and

Treatment	I_b (mm hr^{-1})	c	n
SF-1	25.4	8.36	0.57
SF-2	9.5	2.60	0.59

3.2 Duration of application and amount of supplied water

The water flow test was conducted from July 25th to 27th, 2017. The duration of application for each furrow, and time taken for the water to advance every 10 m was measured at three furrows.

Table 5 Duration of application

Inflow rate	Plot	SF-1		SF-2		Total (s)
		Length (m)	time (s)	Length (m)	time (s)	
5Ls^{-1}	F5.0C	100	1,148	0	0	1,148
	F5.0S	50	462	100	930	1,392
1.7Ls^{-1}	F1.7C	100	3,289	0	0	3,289
	F1.7S	50	1,236	100	1,431	2,667
	F1.7C-50	50	1,299	0	0	1,299
	F1.7S-50	25	374	50	640	1,014

The irrigation times of each treatment are listed in **Table 5**. The irrigation times are the averages of the values measured at three furrows. The irrigation time of F1.7C-50 was obtained using the data of F1.7C up to 50 m. In the case of inflow rate of 5 Ls^{-1}, the total duration of F5.0S was 21% longer than that of F5.0C. In contrast, the total duration of F1.7S was 19% shorter than that of F1.7C. And in the case of 50 m of furrow length, total duration of F1.7S-50 was 22% shorter than F1.7C-50.

The amount of supplied water and application efficiency for each plot are shown in **Table 6**. In this study, the volume of Required Water (*vRW*) was calculated assuming that the width was 0.9 m (ridge and furrow), the depth was 0.0272 m (*RW*), and the length was 100 or 50 m. The application efficiency is defined as the ratio of *vRW* to supplied water amount and we assumed that all supplied water infiltrated into the ridge and furrow. Regarding the inflow rate of 1.7 Ls^{-1}, the applied water amount for 50 m by conventional (F1.7C-50) was used as the data for F1.7C up to 50 m.

Table 6 Amount of supplied water and application efficiency

Inflow rate	Plot	Supplied water (m^3)	vRW (m^3)	Application efficiency (%)
5 Ls^{-1}	F5.0C	5.74	2.45	43
	F5.0S	6.96	2.45	35
1.7 Ls^{-1}	F1.7C	5.59	2.45	44
	F1.7S	4.53	2.45	54
	F1.7C-50	2.21	1.22	55
	F1.7S-50	1.72	1.22	71

Application efficiency of F5.0S was 8% lower than that of F5.0C. Contrarily, application efficiency of F1.7S was 10% higher than that of F1.7C, and that of F1.7S-50 was 16 % higher than that of F1.7C-50. These results suggest that the high inflow rate (5 Ls^{-1}) did not have a water-saving effect on 100 m furrow length.

3.3 Water advance curve

The water advance curves for SF-1 and SF-2 in each inflow rate are shown in **Fig. 6**. The water advance constants obtained by regression analysis are listed in **Table 7**.

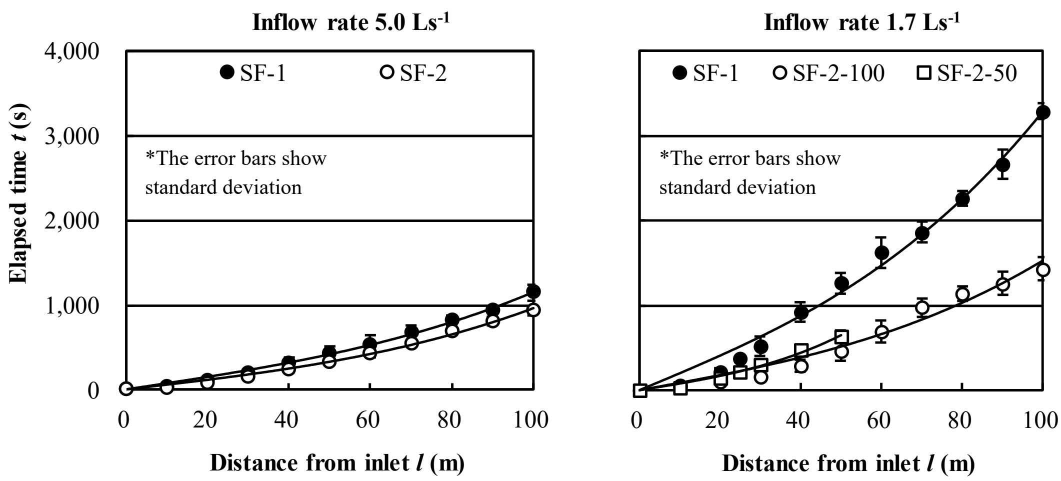


Fig. 6 Water advanced time in SF-1 and SF-2 at every 10 m

Table 7 Water advance constants *a*, *b*

Inflow rate	Length (m)	Treatment	a	b
5.0 Ls^{-1}	100	SF-1	0.0004	7.23
	100	SF-2	0.0004	5.51
1.7 Ls^{-1}	100	SF-1	0.0013	19.88
	100 (wet 50)	SF-2	0.0007	8.63
	50 (wet 25)	SF-2	0.0022	7.67

At an inflow rate of 5.0 Ls^{-1}, the effect of SF-1 on SF-2 advance time was not large, and arrival time at 100 m of SF-2 was just 218 seconds (19%) shorter than that of SF-1. On the contrary, in 1.7 Ls^{-1}, the arrival time at 100 m and 50 m of SF-2 was shorter by 1,858 (56%) and 659 (51%) seconds, respectively. These results indicate that a 100 m furrow length is not suitable for shortening the water advance time under high inflow rate.

3.4 Estimation of furrow infiltration

The amount of cumulative infiltration water in furrows was estimated using the Kostiakov formula (Eq.1) and water advance formula (Eq.3), which was obtained from inflow and furrow infiltration test results and formula (Eq.4). The target for estimation was the time for the irrigation water to reach the end of the furrow. Therefore, in this study, recession time after water supply was not considered. For this reason, there was no infiltration at the end of the furrow. The distribution of cumulative infiltration for each treatment is shown in **Fig. 7**. Cumulative infiltration and amount of infiltration loss are shown in **Table 8**. We define infiltration loss as the amount of water that infiltrated more than *RW* (27.2 mm). Loss ratio is defined as the ratio of infiltration loss to *vRW*.

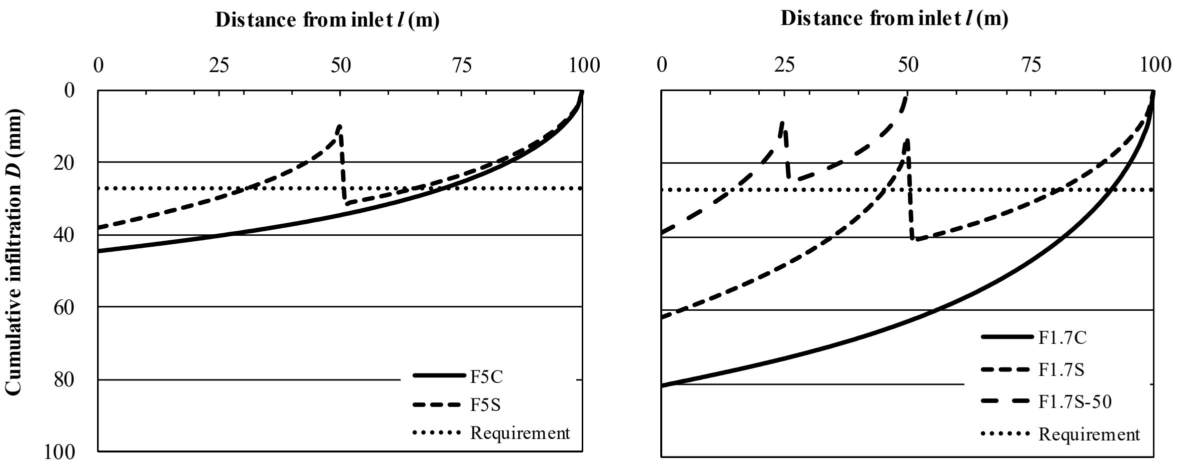


Fig. 7 Distribution of cumulative infiltration water during irrigation time

Table 8 Amount of cumulative infiltration water and infiltration loss during irrigation time

Inflow rate	Plot	vRW (m^3)	Infiltration (m^3)	Loss (m^3)	Loss ratio (%)
5 Ls^{-1}	F5.0C	2.45	2.86	0.64	26
	F5.0S	2.45	2.26	0.20	8
1.7 Ls^{-1}	F1.7C	2.45	5.22	2.85	116
	F1.7S	2.45	3.32	1.05	43
	F1.7C-50	1.22	1.34	0.27	22
	F1.7S-50	1.22	1.01	0.09	7

As mentioned above, at an inflow rate of 5 Ls^{-1}, the volume of supplied water was large. However, if infiltration time was limited during the irrigation period, the infiltration loss was small, and furthermore, simplified SF could reduce infiltration loss. An inflow rate of 1.7 Ls^{-1} resulted in simplified SF showing a clear water saving effect. The effect of F1.7S-50 was larger than that of F1.7S. However, the infiltration loss of 1.7 Ls^{-1} was larger than that of 5 Ls^{-1}. This result indicates that shortening furrow length might be an effective way to save water using simplified SF with a low inflow rate; in contrast, it is necessary to extend furrow length with a high inflow rate.

4. Conclusion

In the study, we studied inflow rate and furrow length of simplified SF. First, from the infiltration tests, we confirmed that preliminary water supply to the furrow effectively lowers the permeability of the furrow. Furthermore, we found that a high inflow rate (5 Ls^{-1}) did not save water when applied to a furrow length of 100 m. We presumed that irrigation water could rapidly reach the ends of the furrows, but the total volume of water applied might increase. In contrast, a low inflow rate (1.7 Ls^{-1}) applied to furrow lengths of 100 m did save water with simplified SF. Water conservation was even greater with short furrow length (50 m). However, if infiltration time was limited during the irrigation period, infiltration loss was reduced at both inflow rates. This result shows that the simplified SF (which divides a single irrigation cycle into two phases with a one-day interval) can reduce infiltration.

Simplified SF would also be useful when inflow rate is insufficient for furrow length. In practice, it is difficult to control inflow rates in the field in Uzbekistan owing to a lack of equipment and labor force. Therefore, to practically apply simplified SF, if the irrigation water in flow rate can be calculated, furrow length can be adjusted. If it is difficult to adjust the furrow length, so as an alternative, it would also be effective to adjust the timing of stopping of the water supply. For example, in the case of a high inflow rate, water supply could be stopped before the water front reaches the end of the furrow to reduce excessive water supply. On the contrary, according to the estimation of furrow infiltration, the *RW* was not fulfilled in the downstream area, and this may cause water stress in cotton. As a control measure, it would be effective to adjust the time of stopping the water supply.

Further studies involving an intermediate flow rate (3.0 Ls^{-1}) and on the timing of stopping water supply are necessary to identify suitable conditions for enhancing water conservation effects of simplified SF. In addition, although simplified SF is expected to save water, it is necessary to understand soil salinity distribution when it is applied.

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Subject 2: Mitigation of Soil Salinization

Subject 2: Mitigation of Soil Salinization

A Trial of Desalinization by Using a Mole-Drain in the Republic of Uzbekistan

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Summary

Irrigated farmland in the Syrdarya Region of the Republic of Uzbekistan, the area of salt accumulation in the soil is 98%. Leaching is being implemented as a measure to remove the salt in the farmland. However, it does not work well in the central part of the farmland far from the drainage channel and the vicinity of the water channel where the salinity concentration in the soil remains high and the groundwater level remains high because the drainage function is low. We introduced shallow subsurface drainage, which is generally used in the farmland in Japan, as a counter measure to salinity into this region. We adopted a new mole drain or Cut-drain system, which is an inexpensive drainage improvement technology developed in Japan.

We determined that the Cut-drain machine is greatly restricted under dried soil conditions in the arid areas. When using a Cut-drain system, it is desirable that the soil surface becomes dry and the soil in the lower layer holds enough water to have plasticity after the leaching and even after the rainy season. The application of the Cut-drain for leaching in Uzbekistan was confirmed, because it was proven by Cut-drain with the formation of the cavity and the discharge from the outlets partially. However, it requires improving measures against the collapse of the cavity at the time of leaching and the increase of leaching effect.

Key words

Mole-drain, High groundwater level, Subsurface drainage, Salt-accumulation, Desalinization, Dryland, Uzbekistan

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1. Introduction

A stable food supply to cope with the rapid growth of the world's population is essential. Highly productive irrigated agriculture plays a major role in world food production. Irrigated agricultural farmland accounts for approximately 18% of the total agricultural land area (1.5 billion ha) in the world and produces 40% of all agricultural food products (Yamamoto, ed., 2008). Approximately 60% of the irrigated areas are in arid regions where salt accumulates in the soil as the side effect of irrigation (secondary salinization). This is due to the excessive input of irrigation water into soil which contains salt. In addition, poor drainage management triggers rising groundwater levels (Hatcho et al., 1998).

In the arid and semi-arid regions of Central Asia, large scale irrigation has developed, with both the Amu Darya River and the Syr Darya River as the main water sources, and as a result, irrigated farmland has expanded (Tsutsui, 1996). Of the irrigated farmland in the Syrdarya Region of the Republic of Uzbekistan, the area of salt accumulation in the soil is 98% (280 thousand ha). Leaching is being implemented as a measure to remove the salt, and because of that, we can observe the increased effluent water in its volume and the salt concentration in the drainage channel. Therefore, it is considered likely that salt leached by leaching drainage is flowing out to drainage channel. However, it does not work well in the central part of the farmland far from the drainage channel and the vicinity of the water channel where the salinity concentration in the soil remains high and the groundwater level remains high because the drainage function is low. If an adequate drainage facility in farmland cannot be obtained, will be necessary to improve the drainage water draining down to the lower, more permeable soil layer when leaching.

With the assistance of the Ministry of Agriculture, Forestry and Fisheries, the Japan International Research Center for Agricultural Sciences (JIRCAS) conducted studies on measures against salinization by groundwater control in the Syrdarya Region. After the studies, we will introduce shallow subsurface drainage, which is generally used in the farmland in Japan, as a counter measure to salinity into this region. It will prevent the accumulation of salt into the soil and eliminate the salt from the soil. Because it requires a large amount of funding to develop the construction of the full-fledged subsurface drainage network, we adopted a new mole drain or Cut-drain system, which is an inexpensive drainage improvement technology developed by the Institute for Rural Engineering, NARO in Japan (Kitagawa et al., 2014).

In this report, we outline the Cut-drain system which has been introduced in the Republic of Uzbekistan as a case study, provide the results of the test Cut-drain system construction and discuss future problems.

2. Overview of Cut-drain system

2.1 Development background and history

In Japan, the increased productivity of soybean, wheat, and vegetables is provided by the multiple use of paddy fields. Previously, it was a prerequisite to improve drainage by switching the paddy field to farmland. The most effective drainage of agricultural farmland is the installation of a main drain, which is buried with a perforated pipe as a sub-lateral drain. It is also necessary to construct a supplementary drain such as a mole drain, which crosses over the main drain and subsoil breaking. These methods maintain and improve the drainage function of the main drain. This project is being promoted by a public project in Japan, and the main drain can certainly be seen as a significant improvement to farmland drainage. However, it is expensive, and it is impossible to make for a large area of farmland in a short period. On the other hand, simple mole drains or subsoil breaking improves drainage performance, but it has low durability and inferior drainage performance compared to the main drain.

The Cut-drain system works with water flow cavities. It has been put to practical use, and farmers can quickly and easily install it without any special materials. It works similarly to water flow cavity that are almost 60 cm depth and the same discharge capacity as a main drain.

2.2 Feature of construction method

The distinctive feature of the Cut-drain system is its unique drilling method (**Fig. 1**). Cut two blades (front blade (a) and rear blade (b)) are inserted into the farmland to form a rectangular soil mass, then lifted by 10 cm, creating a gap just below the groove by push-up blade (c). By using the side-cutter (d) a 10-cm square soil mass is then moved from the side of the space into the space below the groove, thereby forming a rectangular water flow cavity of a mole hole (e).

The Cut-drain system attaches a mechanical unit to a tractor and runs it on the farmland to form a water flow cavity at a deep position in the soil. It is a simple technology that farmers can handle skillfully. It is sometimes used in the cavity as a supplementary drain that crosses and connects to the existing main drain. Occasionally, the blades units are inserted into the drainage ditch beyond the ridge and the cavity is used as a subsurface drainage to remove excess water permeated by opening a water passage hollow at the dike slope of the drainage channel (**Fig. 2**).

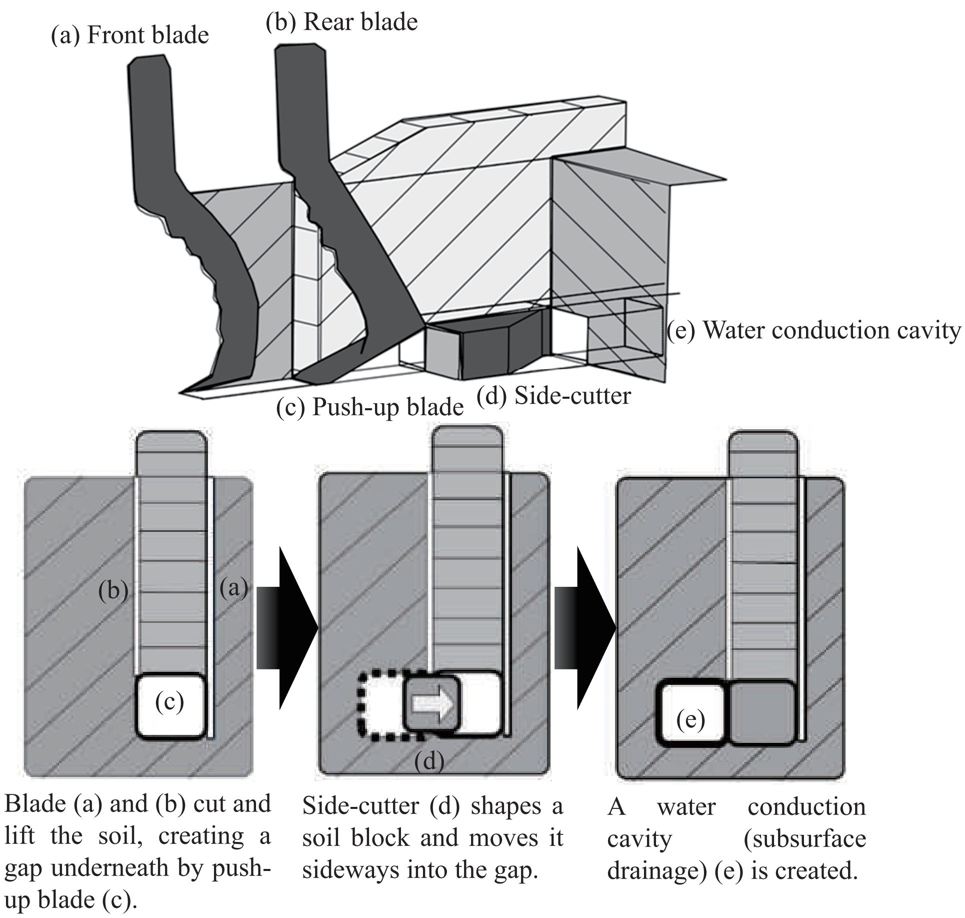


Fig. 1 Structure of Cut-drains

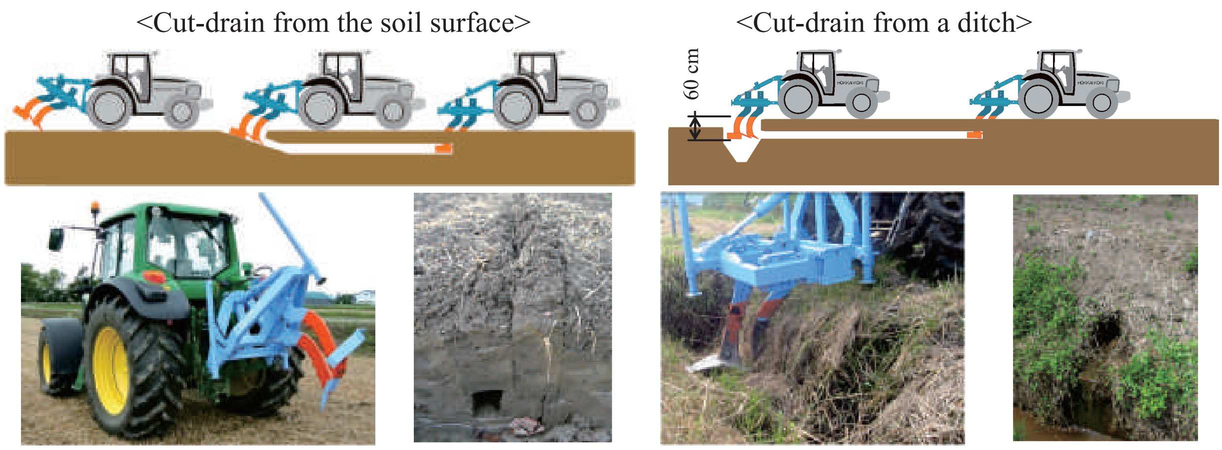


Fig. 2 Drilling method of Cut-drain

2.3 Installation effects and cavity sustainability in wet farmlands

The Cut-drain system used in the field in Japan shows the most drainage volume discharged from the perforated water flow cavity which may meet 5 mm h^{-1} at maximum, and has adequate function, similar to subsurface drainage. As long as the water flow cavity is maintained, which will eliminate surface water stagnation by improving drainage, the roots of the crop in the field are expected to develop and its growth and the crop yield will be improved. The Cut-drain system does not use a pipe, so it is necessary to consider the formability of the cavity at the time of construction and the fall of the soil due to water flowing in the cavity. The applicability of the Cut-drain system in Japan is highly preferred in clay and peat soil (**Fig. 3**).

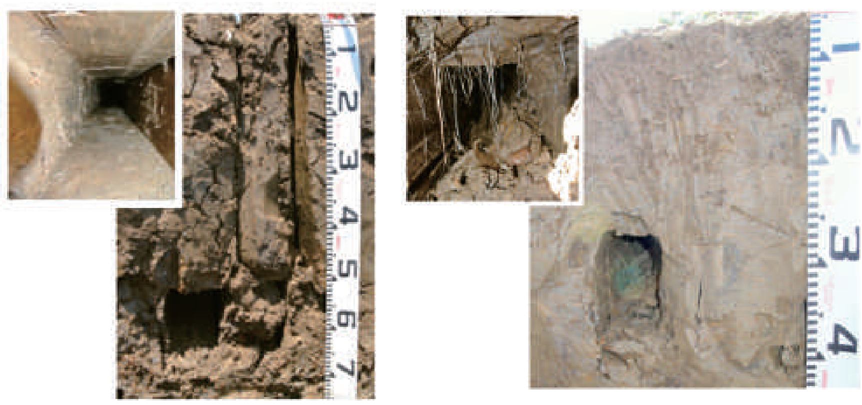


Fig. 3 Profile of Cut-drain

Conversely, it cannot be used in soils of S, LS, SC, SCL, SL, SiC, SiCL, SiL (soil texture classification of the International Society of Soil Science standards) with sand or high silt content. L has a short durability life and it needs to be rebuilt every few years. The main farmlands appropriate for the Cut-drain are rotational paddy fields, upland fields, and grassland. Paddy fields necessarily require ponding, and therefore, it is used as a supplementary drain combined with the main drain in which a relief well to control drainage is installed.

3. Utilization of Cut drains in Uzbekistan

3.1 Drainage technology in Uzbekistan

In the Syrdarya Region, open drainage is approximately 3 to 4 m depth, deep subsurface drainage is 2.5 to 3.0 m depth, and vertical drainage is a facility for direct groundwater pumping. These drainage facilities have mainly been constructed since the 1960s to control the groundwater level. The current problems that are occurring are 1) that sediment is deposited in the open drainage, 2) that the subsurface drainage outlet is clogged, and 3) that the vertical drainage operation efficacy declines. There are many challenges to controlling groundwater, and despite the financial constraints, the Uzbekistan government is also conducting drainage maintenance of drainage, while simultaneously conducting renewal projects and new construction projects to secure drainage functions (**Fig. 4**).

Construction of subsurface drainage (New construction project with financial assistance from aid agency)

Existing vertical drainage (Power costs are high and operating hours are limited)

Fig. 4 Deep subsurface drainage and vertical drainage

3.2 Cut-drain system in Uzbekistan

It is apparent that subsurface drainage is effective in Japan when desalting salt damaged farmland (Kaneko et al., 2002). Furthermore, it has been shown that the installation of subsurface drainage is effective for leaching with waterlogging in the farmland, even in arid areas (Abou et al., 2005). We have installed two shallow subsurface drainage (sub-lateral drain depth approximately 1 m, extension length 200 m, with rice husk as the hydrophobic material) as a technology to eliminate the excess of infiltration water in the testing field in the Syrdarya Region, and we studied the effect on the field. However, it was limited to installing the main drain in the same manner as that of Japan regarding material supply and budget, but unlike Japan, to install a main drain in Uzbekistan. In order to reduce construction costs and the use of material, the Cut-drain system was introduced on a trial basis to examine its applicability. The outline of the construction of the Cut-drain system and the leaching effect has been clarified and will now be explained.

3.2.1 Problems in the construction of Cut-drain

(a) Capability of tractor

Agricultural equipment such as tractors are imported from Europe. The basic functions such as hydraulics and PTO (rotational power take-off) of the tractor can be utilized in Uzbekistan. However, some frequently-used tractors had functions that often broke down, but those parts continued to be used without renewing them for emergency measures such as welding. A tractor was observed in the Syrdarya Region which could not be subtly controlled, for example horizontal or height adjustment.

(b) An appropriate period of construction viewed from soil moisture

The soil moisture condition in the test field is shown in **Fig. 5**. In the brown lowland soil (soil texture: L) found in the test field, the soil moisture is low to the lower layer in the dry season and does not have plasticity. Immediately after the dry season in October 2014, when attempts were made to connect the drainage ditch for the Cut-drain, the soil did not deform even when the Cutting blade was brought into contact with the soil (depth of 70 to 90 cm), and the Cutting blade could not be inserted. In contrast, when this was attempted with a slightly high viscosity light gray soil (soil texture: CL) in which the soil moisture was also high, it was able to be drilled properly (**Fig. 6**). Afterwards, three trials were conducted regardless of whether or not the soil moisture condition was acceptable. The trial constructions were conducted firstly at the beginning of the rainy season in November 2014, the second in December 2014 before leaching, and the third trial was in April 2015 after leaching in the trial field under the same construction conditions.

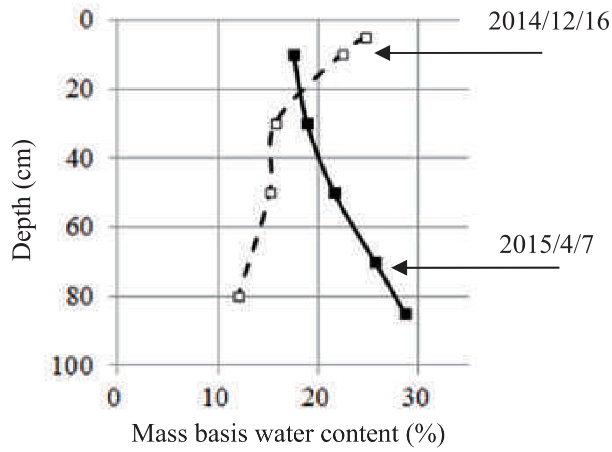


Fig. 5 Soil moisture condition

Fig. 6 Drilling situation of the Cut drain operated in Uzbekistan

During the second construction in December, the tractor wheels occasionally slipped when pulling the mechanical unit because the soil surface was wet, and the earth was crushed. Moreover, even if the Cutting blade could be inserted, a perforated portion could not be formed because of inadequate plasticity due to dryness in the lower soil layer. The soil surface was firmly dried in the construction in April and the machine unit could be towed without any problem and there were the appropriate perforated portions formed. The characteristics of the soil moisture condition significantly affected the workability and hole formation. Regardless of the dry weather in Japan, the drying of the subsoil maintained the same condition of the plasticity and therefore, the use of the Cut-drain system was not a major problem. However, we determined that the Cut-drain machine is greatly restricted under dried soil conditions in the arid areas. When using a Cut-drain system, it is desirable that the soil surface becomes dry and the soil in the lower layer holds enough water to have plasticity after the leaching and even after the rainy season.

3.2.2 Problem of using a Cut-drain system for leaching

(a) To scour by an excessive inflow of leaching water

Leaching in the Syrdarya Region is mainly conducted between December and January. In preparation for leaching, 30 to 50 cm high ridges are made and then the farmland is divided into sections. According to the recommendations of the salt damage measures implemented by agencies of the Uzbekistan Government, its shape is divided into 50 m per side if the terrain gradient is less than 1/500, and the amount of water for leaching is set to 2,500 to 4,000 m^3 ha^{-1}. Leaching water is ponded into the compartment and it is allowed to stay there for two weeks, where it is left to naturally permeate into the subsoil.

Leaching in the test field was carried out on 27 December, 2014 and 15 January, 2015. There was a significant difference between a large amount of discharge in some ditches and less discharge in other ditches under the same the Cut-drain system conditions. After the profiles of the Cut-drains were checked on the construction lines, cavity collapses were observed. There is a possibility that infiltrated water flowed down into the cavity through the vertical groove which was made by the blade of the Cut-drain. In contrast, at two normal subsurface drainage outlets, discharge was observed after leaching (**Fig. 7**).

Cut drain (December 30)
3 days after leaching

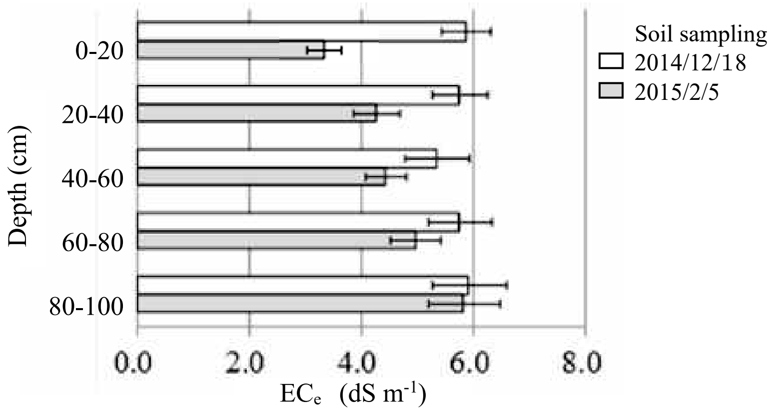
Pipes (2 m) were inserted to protect the Cut-drains

Shallow subsurface drainage (January 3)
7 days after leaching

Fig. 7 State of discharging from outlets after leaching

(b) Effect of leaching to reduce soil salinity

We took the sample of soil which was divided into five layers of depth (0-20, 20-40, 40-60, 60-80, 80-100 cm) and analyzed that how much salt remained in each soil layer before and after leaching. When looking at EC_e (electrical conductivity of the saturated extract of soil), the salt was mostly eliminated on the surface layer after leaching (**Fig. 8**).



Leaching took place on December 27, 2014.
EC_e is an estimated value converted from $EC_{1:1}$
Error width is standard error (each layer n = 8)

Fig. 8 Soil EC_e before and after leaching

In the test field, there was a hard soil layer 30 to 50 cm below the ground surface, which prevented the permeation of leaching water. At the time of leaching, a preferential flow was mainly generated through the Cut drain vertical groove. Hence, the amount of penetration below the hard soil layer was reduced. Therefore, it is considered that the leaching of salts mainly occurred at the surface (upper layer than the hardpan). We needed a counter measure to permeate down the leaching water below the lower layer of the hardpan to reduce the salinity in the subsoil.

The application of the Cut-drain for leaching in Uzbekistan was confirmed, because it was proven by Cut-drain with the formation of the cavity and the discharge from the outlets partially. However, it requires improving measures against the collapse of the cavity at the time of leaching and the increase of leaching effect. If the Cut-drain as the supplementary drain, which is easy to use for repeated re-installation on the field is used, it could also be expanded to the main drain and save construction cost. Installing a combination of the main drain and supplementary drain as the Cut-drain system in the Syrdarya Region, similar to the paddy fields in Japan, should be considered.

4. Conclusion

A drain drilling technique or ‘Cut-drain’ needs to be constructed with soil moisture conditions suitable for perforation formation. It needs to cope with excessive drainage, which leads to the collapse of the perforated cavity. There is also the problem that improvement of permeable drainage through the hard soil layer is necessary. However, the simple structure and novel construction methods are highly anticipated by farmers, engineers, farmer instructors, and agricultural machinery makers and distributors in Uzbekistan. In the future, it will be important to develop the technology suitable for the local area for solving the problems, in conjunction with Uzbekistan's engineers. The combination of the main drain and perforated cavity is a typically used drainage technology in Japan, which eliminates the infiltration water properly. In Uzbekistan, there are many areas where farmland with salt accumulation and fields with reduced drainage functions are the main obstacle to agricultural productivity. Those places certainly require the use of inexpensive drainage with improvement technology, such as that developed in Japan.

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*The above article was translated and reprinted from “Water, Land and Environmental Engineering, Vol. 83, No. 7, pp. 541-544 (2015)”, published by the Japanese Society of Irrigation, Drainage and Rural Engineering.

Problems and Measures for the Adoption of Cut-drain and Its Applicability to Soil Conditions in Uzbekistan

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Summary

Secondary salinization of irrigated lands in Uzbekistan has been caused by excessive irrigation and rising groundwater levels due to the malfunction of drainage systems. Measures such as drainage system maintenance or leaching has been conducted, but there are fields where salinity levels remain high. The use of a shallow subsurface drainage system has been proposed to ensure the complete removal of percolation water after leaching, but it is considered to be an expensive option. Therefore, the possibility of introducing a drain drilling machine (Cut-drain) which has been developed recently in Japan, was studied. Employing Cut-drain has presented some problems because it rises up to the soil surface and causes the occurrence of preferential flow under dry soil conditions. In this study, we examined the soil moisture conditions suitable for the construction of Cut-drain and the effectiveness of a method for mitigating preferential flow. The results showed that there was a borderline soil moisture condition needed in the construction of Cut-drain. More than 9–11% moisture was required in the first soil layer (from the surface to 20 cm below it) and 12–15%, in the second layer (from 20 to 40 cm). Furthermore, it was found that the preferential flow could be mitigated by irrigating the furrows before construction.

Key words

Salinization, Subsurface drainage, Cut-drain, Soil moisture, Preferential flow

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1. Introduction

1.1 Background

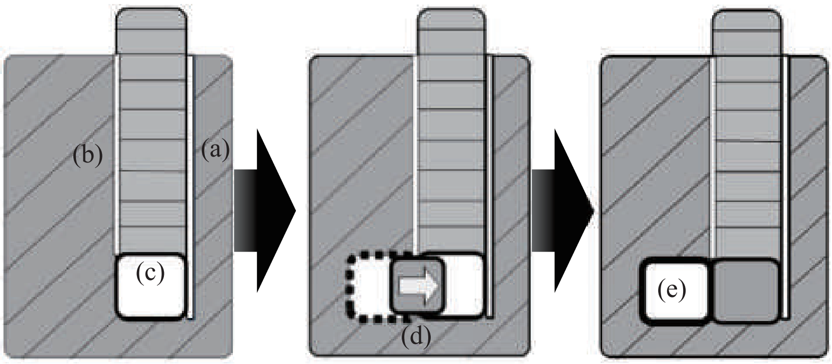
A stable food supply is required to address the world's growing population, and highly productive irrigation agriculture plays an essential role in world food production. Irrigated agriculture represents approximately 20% of total cultivated land but contributes 40% of the total food produced worldwide (FAO, 2015). In arid areas, especially where irrigation is required, the soil salinization of agricultural land is progressing due to excessive irrigation with saline water, water leakage, and rising groundwater tables caused by inadequate management of drainage systems. Salinized farmland accounts for approximately 25% of irrigated areas, including slightly salinized land (Kitamura, 2016).

Irrigated farmlands have expanded in the arid and semi-arid areas of Central Asia since large-scale irrigation development projects were conducted utilizing the Amu Darya and Syr Darya Rivers as water sources (Tsutsui, 1996). The Syrdarya Region of the Republic of Uzbekistan, an arid and semi-arid area, has experienced secondary salinization of irrigated farmland, where facilities such as open channel drainage, deep subsurface drainage and vertical drainage were installed with governmental support. Leaching operation is periodically conducted by mid-sized agricultural enterprises (known as "*Fermer* (farmer)") as a counter measure to directly remove salts.

On-site observations at open channel drainage surrounding irrigated farmland before and after the leaching operation were conducted in winter and have shown that leaching has removed salts from the soil, as demonstrated by increases in the amount of discharge water as well as the saline density in the water after leaching (Okuda et al., 2015a). However, the groundwater level remains high in farmland with malfunctioning drainage systems and in areas far from open channel drainages such as the center of farmland surrounded by open channel drainages and around irrigation canals. Here, the density of salts remains high in soil because leaching water only infiltrates downwards and is not sufficiently drained away from the field.

Shallow subsurface drainage systems are thought to be an effective counter measure in such farmlands to lower the groundwater level, which can reach 50 cm below the soil surface and ensure removal of percolation water with contained salts following leaching (Chiba et al., 2012). The shallow subsurface drainage system requires less labor in construction per unit length compared to deep subsurface drainage systems, however, longer perforated pipes are installed per unit area and so construction is not necessarily less costly than for a deep drainage system. The drain-drilling machine (hereinafter referred to as "the drilling machine"), and the constructed drainage (Cut-drain) have been developed recently in Japan to reduce the construction cost of shallow subsurface drainage (Kitagawa et al., 2010). The drilling machine makes a cavity at approximately 60–90 cm depth using only the traction force of a tractor. Two blades, front and rear (Cutting blades), cut the soil. The bottom blade (push-up blade) lifts up the vertically-long cut soil chunk, and the side-cutter excavates a cavity immediately next to the cavity made by the lifted soil chunk. This method is applicable to relatively firm soils (**Fig. 1** and **Fig. 2**). Employing this method results in a more stable cross-section than cavities made by mole drains placed immediately underneath the construction line. Cut-drains can be applied to the following three drains: (1) direct drainage system that connects the cavity with open ditch drainage, (2) supplementary drain that connects the cavity with main drain (perforated pipe and hydrophobic materials such as rice husk) and (3) drilling and pipe drainage in which drainage pines are installed.

Fig. 1 Drain-drilling machine and cavity of Cut-drain



Blade (a) and (b) cut and lift the soil, creating a gap underneath by push-up blade (c).

Side-cutter (d) shapes a soil block and moves it sideways into the gap.

A water conduction cavity (subsurface drainage) (e) is created.

Fig. 2 Process of making cavity of Cut-drain

Conventional soil layer improving techniques that insert and drag machinery in soil include subsoil breaking and mole drain systems using drilling machines. Subsoil breaking aims to decrease soil hardness by breaking hard soil layers and increasing permeability and plays a major role in allowing the expansion of crop root systems in arid regions. Mole drain systems aim to form a water-running cavity and are employed in Europe and in Asian monsoonal countries to drain water but, knowledge of cavity construction for arid areas is very limited. It is extremely difficult to form a firm cavity when it is possible to break soil, because the construction employing insert-and-drag style machinery would face large tractive resistance, particularly in areas where the soil has low moisture content and cavities cannot be constructed below the plastic limit. Therefore, a certain level of soil moisture content is needed to be able to construct cavities for mole drains. Very little research, however, has studied the drilling machine construction mechanism in terms of soil moisture content.

1.2 Problems with Cut-drain and research objectives

1.2.1 Problems with Cut-drain application

Previously, we constructed experimental shallow subsurface drainage (within 90 cm depth) in the Sydarya Region of Uzbekistan with the aim of removing percolating water following leaching as well as groundwater near the soil surface. However, there was a phenomenon where a cavity could not be constructed because the drilling machine was lifted above the soil surface during the passage of the cutting blade through the soil (Okuda et al., 2015b).

Furthermore, some cavities collapsed after irrigation or leaching operation in the fields where Cut-drains had been constructed. There were some differences in the conditions of the collapse, whereby in some cases part of the cavity remained, and in others the cavity completely collapsed. Soil of the collapsed parts were soft and so it was thought that these partial cavities would retain some function in water drainage despite having a decreased cross-sectional area. However, a collapse would greatly undermine its function. The collapse was thought to have occurred because of a large amount of preferential flow of irrigation and leaching water entering the cavity and the soil collapsing under its own weight following the wall of the cavity being eroded. Preferential flow was thought to have occurred through some of the rough cracks and gaps created by the passing cutting blade. The soil of the field researched in this study had low water permeability and hence, preferential flow could increase the runoff rate and facilitate draining through subsurface ditches. In the shallow subsurface drainage system intended to remove percolation water after leaching, preferential flow which results in excessive water leaking would not only decrease the cross-sectional area of drainage, but also lower the effect of salt leaching because the time during which leaching water and soil is in contact will decrease.

Therefore, the problems in applying Cut-drains in the Syrdarya Region are 1) lifting of the drilling machine, and 2) cavity collapse following construction.

1.2.2. Research objectives

In Japan, soil plasticity does not usually decrease as the lower soil layer dries and hence it is rare that a drilling machine cannot be operated. This research aims to clarify the soil moisture conditions for which the drilling machine does not lift, and the tractor can be operated such that the cavity can be constructed at the desired depth in a stable manner. In addition, a method was tested to prevent excessive preferential flow and so avoid the degradation of drainage function and decrease in removed salt during leaching.

2. Overview of the research area

Uzbekistan is surrounded by five inland countries, Kazakhstan to the north, Kyrgyz and Tajikistan to the east and southeast, Afghanistan to the south and Turkmenistan to the south and west. The area of Uzbekistan is 447 thousand km^2, which is approximately 1.2 times that of Japan. Desert and steppe areas occur in the west and account for 60% of national land, and the Tian Shan Range and the Pamir Mountains occupy the eastern part of the country, forming mountains and plateaus. The Amu Darya and

Syr Darya Rivers flow in the south and north of the country into the Aral Sea. The climate is continental, and temperatures are highly variable, with summers hot and dry and winters cold and wet. Annual precipitation is 100–250 mm in the desert areas, 200–545 mm in the foot of mountains or plain areas and more than 400 mm in the mountain areas (FAO, 2006). The Syrdarya Region is in the foothill plains area and is classified as a semi-arid climate because the dryness index is 0.32 (estimated value) and precipitation is 335 mm (average of previous five years). In summer, the temperature can exceed 40 °C, in winter it can be below -10 °C, and the rainy season of October–April brings precipitation.

Of Uzbekistan's farmland, 4.3 million ha had irrigation facilities in 2014 and according to interviews conducted with the Farmers' Council, 47% of irrigated farmland has experienced salt accumulation (EC_e > 2 dS m^{-1}). In the Syrdarya Region, 98% of irrigated farmland (280 thousand ha) has been damaged by salt accumulation. Apart from the Syrdarya Region, almost all irrigated farmland has experienced salt accumulation in the Xorazm Region, and more than three-quarters of irrigated farmland in the Bukhara, Navoiy, and Jizzakh Regions and the Republic of Karakalpakstan have experienced salt accumulation.

Farmland in the Syrdarya Region is located between branch irrigation canals typically made of U-shaped concrete and branch open channel drainages made of soil (3.0–4.5 m depth). The width between the irrigation canal and drainage is approximately 450 m in most farmland. Temporary water ditches are constructed to irrigate between furrows before the irrigation period. The farmland appears to be evenly elevated, however, there are many undulations and hence, irrigation water is not efficiently distributed, and this is one of the reasons for excessive irrigation. In addition to irrigation canals, deep subsurface drainage system (2.5–3.0 m depth) or vertical drainage (a drainage system in which pumping pipes are installed to lift groundwater from the deep soil layer) are introduced to control the groundwater level. Farmlands are nationally owned and leased to farmers, on which cotton, and wheat are produced through contracts as a part of governmental production schemes.

The research sites are farmland in the Syrdarya Region, cultivated by farmers of the local Water Consumers' Association (WCA) as follows: Axmedov WCA of Mirzaabad District, and Yangiobad WCA and Bobur WCA of the Oqoltin District (**Fig. 3**). The research sites are alluvial soil which has low permeability, and the soil profile of 1 m depth mainly consists of loam soil (L), sandy loam soil (SL) and clay loam soil (CL), according to the soil texture classification of the International Society of Soil Science standards. Cut-drains can be constructed in L and CL but not SL soil. The soil texture of each WCA slightly differ. Axmedov WCA has L and SL, Yangiobad WCA has L, SL and CL, and Bobur WCA mainly has CL and L. The soil permeability index and dry bulk density of Bobur WCA are shown in **Table 1**.

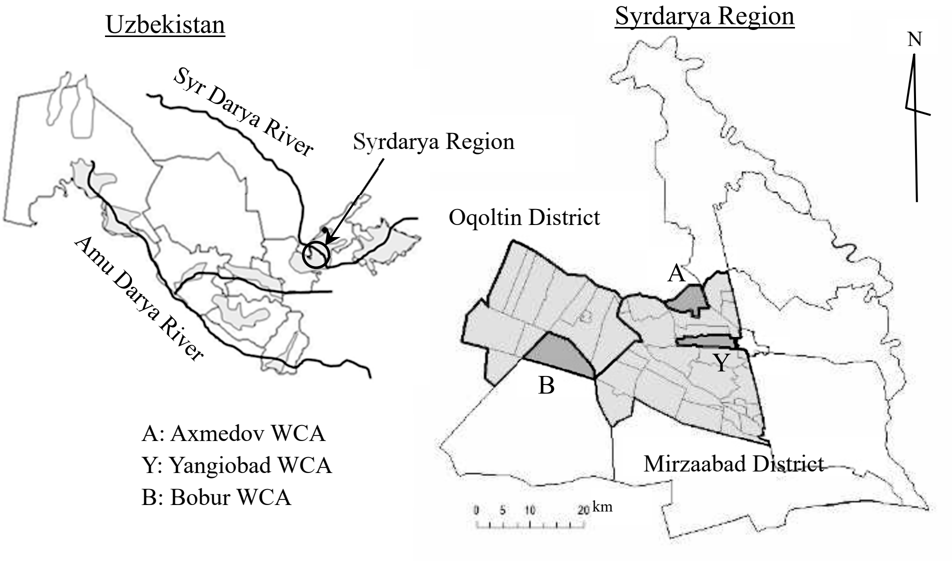


Fig. 3 Location map of research sites

Table 1 Physical properties of soil in the experimental field*

	Soil permeability index ** (cm s^{-1})	Dry bulk density (g cm^{-3})
Top soil (0-20 cm)	1.7×10^{-4}～1.1×10^{-5}	1.59±0.06
Hard pan (30 cm)	1.3×10^{-5}～4.3×10^{-6}	1.71±0.03
Subsoil (40-100 cm)	1.1×10^{-3}～9.1×10^{-5}	1.48±0.06

*) Soil sampling point is Bobur WCA Pakhtakor Farm, October 2009

**) falling head permeability test

3. Research method

3.1 Understanding soil moisture content suitable for the formation of cavities

The soil moisture conditions suitable for Cut-drain construction were studied in the fields of three WCAs by comparing how the cavities were made in different periods of time with different soil moisture contents.

Water content was determined when monitoring mass basis soil moisture content because this is relatively easy to measure and the local engineers in Uzbekistan can easily analyze the acquired soil samples. Soil samples were taken in areas surrounding the Cut-drain construction sites and water content measured by drying the samples at 105 °C for 24 h. Soil layers were classified into five categories: 1) surface soil (0–20 cm depth), 2) a soil layer around 30 cm depth that contains hard soil (20–40 cm), 3) a layer above the Cut-drain cavity (40–60 cm) and 4) two layers below 60 cm (60–80 and 80–100 cm, respectively). Two periods of time were selected which were firstly, after leaching in March–April, and secondly, the dry season, in June–August. March and April are the months before sowing cotton seeds and hence, the surface soil is sufficiently dry for tractors to operate, but some water remains in the lower layers. Soils are dry in June and August, but soil moisture content is relatively stable in irrigated farmland as well as fields with higher groundwater levels.

Cut-drains were constructed using a farmer-owned tractor (Case IH MXM140Pro or New Holland TS130) with a drilling machine attached.

3.2 Experiment on preventing preferential flow

Furrows were irrigated beforehand, where the drilling machine's cutting blades pass, to test a method of constructing cavities at high soil moisture content and investigate its effect in preventing the occurrence of preferential flow. In this method, it was expected that soil pores would fill with soil particles and big cracks would be elastically closed by plasticity of the soil. The experiment was conducted in Axmedov WCA.

The experimental furrow was 10 m long and the Cut-drain was constructed under irrigation conditions as follows:

(a) 10 cm irrigation plot – irrigated with water equivalent to 10 cm water depth, applied in a furrow with width 0.9 m (0.9 m × 0.1 m × 10 m = 0.9 m^3) and the Cut-drain constructed two days later.

(b) 3 cm irrigation plot: irrigated with water equivalent to 3 cm water depth, applied in a furrow with width 0.9 m (0.9 m × 0.03 m × 10 m ≈ 0.3 m^3) and the Cut-drain constructed on the same day.

(c) no-irrigation plot-control; Cut-drain was constructed with no irrigation water applied.

The three treatments, (a)–(c), were applied to three furrows each, making a total of nine furrows. Soil samples were collected before and after Cut-drain construction to measure water content from layers 1-5 as classified previously as 0–20, 20–40, 40–60, 60–80 and 80–100 cm.

Approximately one week after Cut-drain construction, an infiltration experimental plot (1.0 m length) was prepared between furrows to investigate water infiltration. The infiltration experiment was conducted in a total of 18 plots with two plots each on all the furrows of treatments (a)–(c). A gauge (wooden stick with a scale) was installed to measure the change of water depth over time. The change in infiltration rate was observed after irrigating with approximately 10 cm of water. More water was irrigated for further observation if infiltration proceeded in the experimental plot. Furrow banks were covered with plastic and the fields surrounding the experimental plots were also irrigated when the experiment started to prevent horizontal infiltration towards the outside of the experimental plots. In addition, control plots without Cut-drains were situated next to plots with Cut-drains, and irrigation conditions as used for adjacent treatments (a), (b) or (c) were used to allow comparison of their infiltration conditions. Infiltration was observed for approximately 4 h after irrigation started, and an approximate expression was derived from plotting the cumulative amount of infiltration (D) against time (t). The cumulative infiltrations at 30 and 60 min after onset of irrigation were calculated from this expression, and the difference was converted into a value per unit time and considered as infiltration capacity (Kanmuri et al., 2007).

The occurrence of preferential flow was recorded by observing any water flow out to the cavity at the soil profile. An observation pit of 1.0 m depth was dug next to the infiltration experimental plot so that the cavity was exposed to the pit. For the opposite side of the observation pit from the examined exposed cavity experimental plot, the cavity was closed by soil in order to prevent percolating water flowing against the pit (**Fig. 4**).

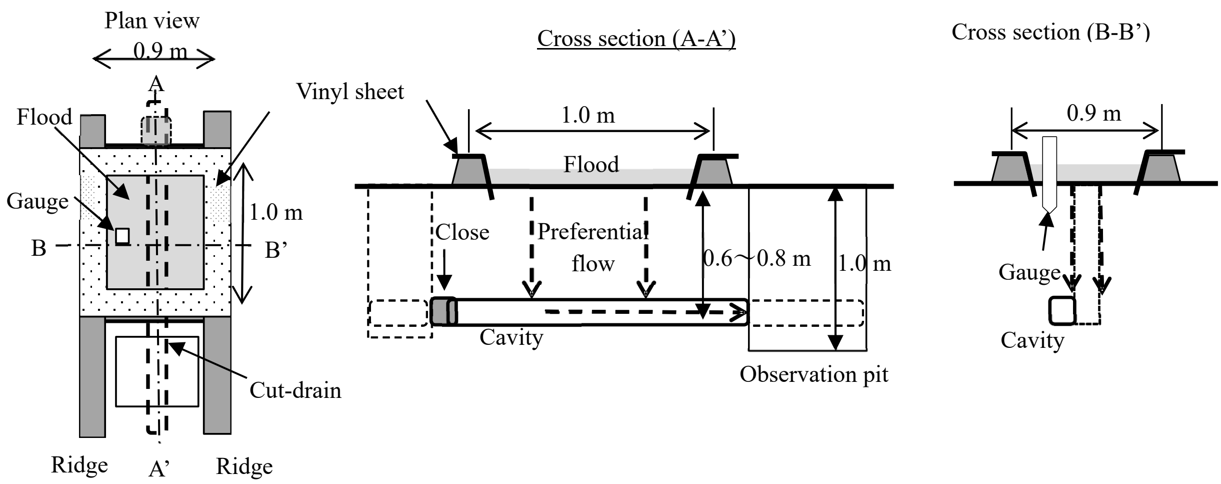


Fig. 4 Drawing of infiltration experimental plan

4. Results and discussion

4.1 Soil moisture content suitable for cavity construction

The results of the construction of Cut-drains in three WCAs and soil moisture content measured at different soil depths (water content) are shown in **Fig. 5**.

Some resistance was observed when inserting the drilling machine into the soil during construction in March–April after leaching and before cotton seeds were sown. The Cut-drain was constructed at a depth of 60–90 cm by adding a load of 100–120 kg to the base frame of the machine. Observation of the soil profile following construction showed that cavities successfully formed in all the plots. Water content of the three WCAs (using averages of each WCA) were 16–18, 18–19, 18–23, 25–29 and 29–31% in layers 1–5, respectively.

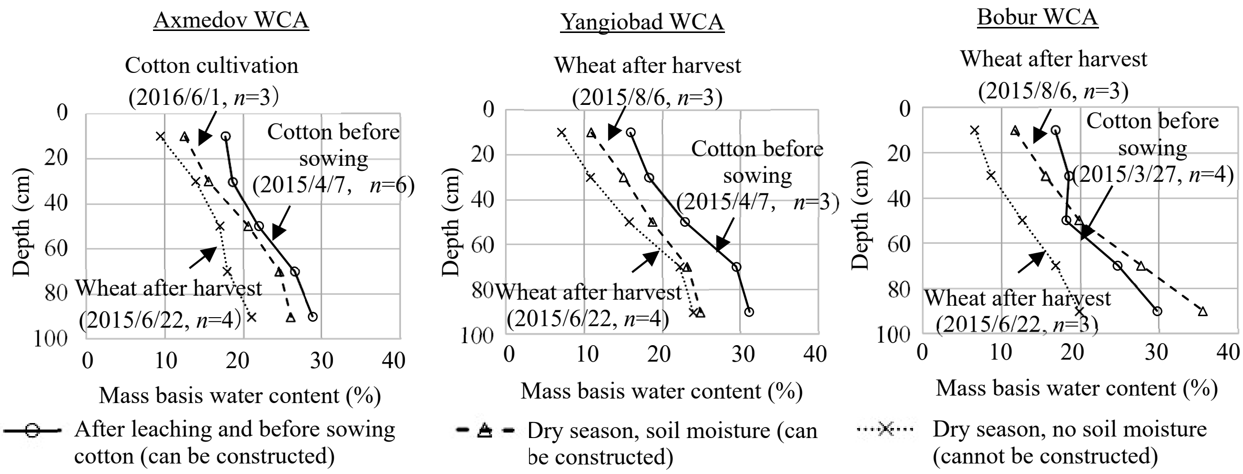
In the field where soil moisture was relatively maintained, it was possible to construct Cut-drains by putting some weight onto the base frame as used in the field before sowing the cotton seeds. The reasons why soil moisture was retained were: 1) leaching water remained in Axmedov WCA, 2) irrigation water was supplied in Yangiobad WCA and, 3) the groundwater level was high in Bobur WCA. When operating the tractor, its wheels were temporarily idling when passing points with hard soil, however, it was able to proceed, and traction was always possible. Upon inspection, it was revealed that cavities were successfully formed in all inspected soil sections. Water contents were 11–13, 15–16, 19–21, 23–28 and 25–36% for layers 1–5, respectively.

When the experiment was conducted on the field after wheat was harvested in the dry season (no irrigation water was applied), it was not possible to construct Cut-drains because the machine lifted, even with weight added to the base frame. Water content decreased by 8% on average compared with those measured before cotton seeds were sown (7–9, 9–14, 13–17, 17–22 and 20–24% for layers 1–5, respectively).

Water contents were lower in fields where Cut-drains were not constructed in the dry season than in fields where Cut-drains were constructed. It was assumed that between the values of water content for the two fields there was a lower limit of soil moisture condition for which Cut-drains could be constructed. The median of water content of both fields in the three WCAs were 9–11, 12–15, 15–19, 21–23 and 24–25% for layers 1–5, respectively (values from Bobur WCA were from the third and lower layers only and the median was calculated using the field where construction was not possible and the field before the cotton seeds were sown where construction was possible). It was estimated that these soil moisture conditions were the lower limits of soil moisture that allows construction of Cut-drains in the research fields.

The tractor was able to run, without the drilling machine attached, on soil where soil moisture was retained on the surface due to irrigation. However, with the drilling machine attached, the wheels were idling, and construction could not continue. The threshold water content was 24%. The tractor wheels were idling temporarily when the tractor operated on the field where surface soil was dry in the dry season because soil was very hard in some places and resistance force was strong.

Therefore, we concluded that the water content similar to that after leaching and before cotton seeds were sown was one of the soil moisture conditions in which Cut-drains could be constructed without any problem in the Syrdarya Region. However, it should be noted that some modifications were required such as adding weight to the base frame, to insert the drilling machine into soil in each season.



Note) Analysis results are shown at the midpoint of each layer

( ) Date is Cut drain construction and soil sampling date, *n* is sampling number

Fig. 5 Soil moisture under construction of Cut-drain

4.2 Experiment on preventing preferential flow

4.2.1 Soil water content when Cut-drain is constructed

The experiment was conducted in Axmedov WCA. (a) The 10 cm irrigation plot was irrigated on 30

May 2016, and (b) the 3 cm irrigation plot was irrigated on 1 June and Cut-drains were constructed on 1 June in all the experimental plots of (a), (b) and the control plots (c) (**Fig. 6**). Water contents of the plots when constructing Cut-drains are shown in **Fig. 7**. Water contents of plots (a) and (b) were 23–24, 20–21, 22, 25 and 27% for layers 1–5, respectively. Compared with plot (c), the corresponding rates were 10–11, 6–7, 1, 0 and 2% higher (**Fig. 7**). There were no significant differences for layers 3–5 among plots (a), (b) and (c), and there was indication that irrigation water affected soil moisture mainly in layers 1 and 2.

(a) Irrigation 10 cm

0.9 m^3 input (5/30)

Cut-drain construction on the second day after irrigation (6/1)

(b) Irrigation 3 cm

0.3 m^3 input (6/1)

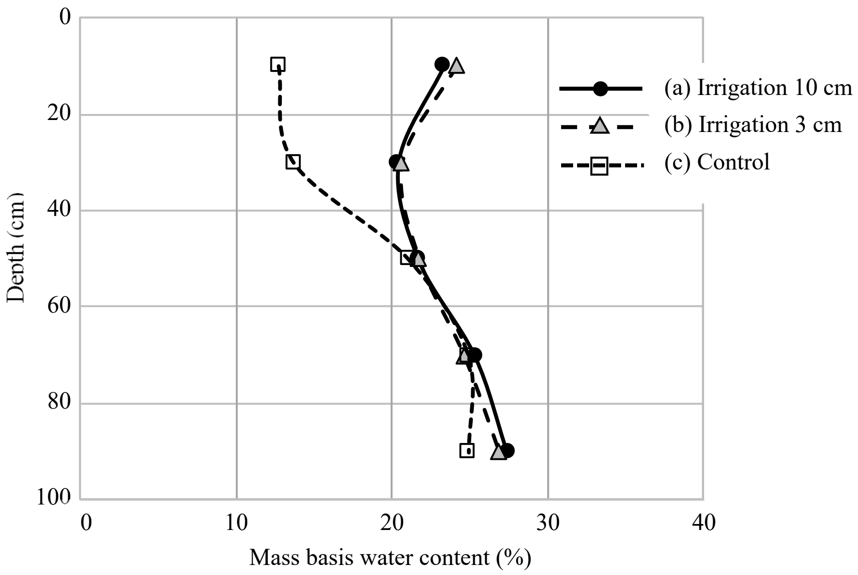
Cut-drain construction on irrigation day (6/1)

(c) Control

Non-irrigation (6/1)

Construction of Cut-drain in dry condition (6/1)

Fig. 6 Cut-drain construction under different irrigation conditions



Note) Analysis results are shown at the midpoint of each layer

Fig. 7 Soil moisture under each irrigation condition

4.2.2 Effect of irrigation on tractor operation

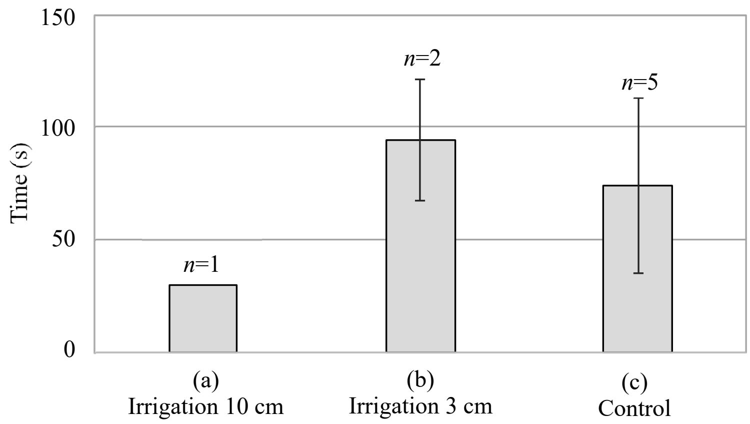
When constructing Cut-drains, a concern is that tractor wheels could be idling when soil moisture content is high in the soil between the furrows where the wheels run. In plot (a), which had high water content, it was expected that soil between furrows where the wheels run would also have a higher water content. Therefore, in plot (a), water content of soil was measured between the furrows next to the irrigated furrows. This showed that the water content of layers 1 and 2 were 12% and 15%, respectively, on the day that soil was irrigated. However, contents increased on the two days following irrigation and layer 1 was 17% and layer 2 was 19%, which is an increase of 4–5% in both layers. These soil moisture conditions were similar to those after leaching and before cotton seeds were sown. There is not considered to be any problem constructing Cut-drains for 10 cm of irrigation, although soil moisture content increased in the surrounding furrows. Furthermore, as an issue of irrigation management, it was expected that water could leak into surrounding furrows when furrows were shallow and the distance between them was short. If soil moisture in furrows where wheels run becomes too high, the wheels could be idling. In the case where the amount of irrigation water at the level of plot (a) is applied, it is necessary to confirm existence of the cross-sectional area for irrigated water as well as to manage the amount of irrigation, to prevent any water leaking.

4.2.3 Conditions in which preferential flow occurs

A water infiltration experiment was conducted 8–9 days after the construction of Cut-drains plots of (a)–(c) (six plots each, making a total of 18 plots). The results showed that eight plots experienced preferential flow after irrigation started, with one plot in (a), two in (b) and five in (c). A large amount of water infiltration was observed.

The irrigated water at experimental plots where preferential flow occurred disappeared very soon after the flow occurred. The periods of time from starting the experiment until preferential flow occurred were within 30–132 s, and no tendency was found such as plot (c) collapsing at an earlier time (**Fig. 8**). Thus, the path of preferential flow and the conditions of soil pores from the surface layer to the cavity is not uniform.

The observation of pits showed that in plots (a), infiltrated water oozed earlier from the upper section of soil than from the cavity, but soon after, water leaked from the cavity. In plots (b), infiltrated water leaked only from the cavity. In plots (c), water leaked from the cavity in four plots, but the remaining plot had no water leaking. The surroundings of this last plot were studied and showed that water infiltrated into the part of the Cut-drain on the other side of the pit, and this was thought to be due to preferential flow. Leaked water was observed in the pits, however, almost all cavities were retained. It is likely that the cavities were retained because of the small amount of water flow.



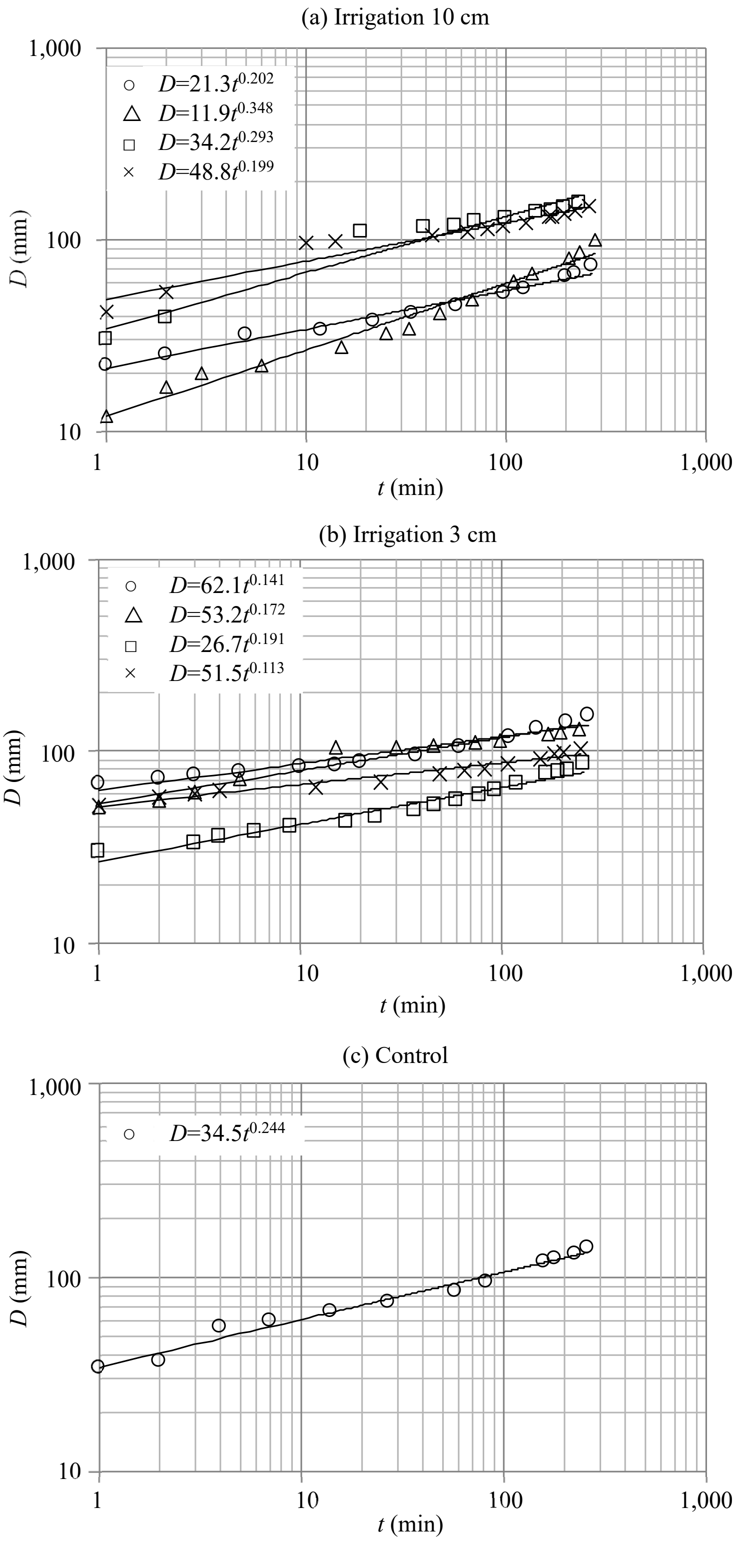
Note) Error bars are standard deviation

Fig. 8 Time required for the incidence of preferential flow in each experimental plot

4.2.4 Conditions of water infiltration where preferential flow was prevented

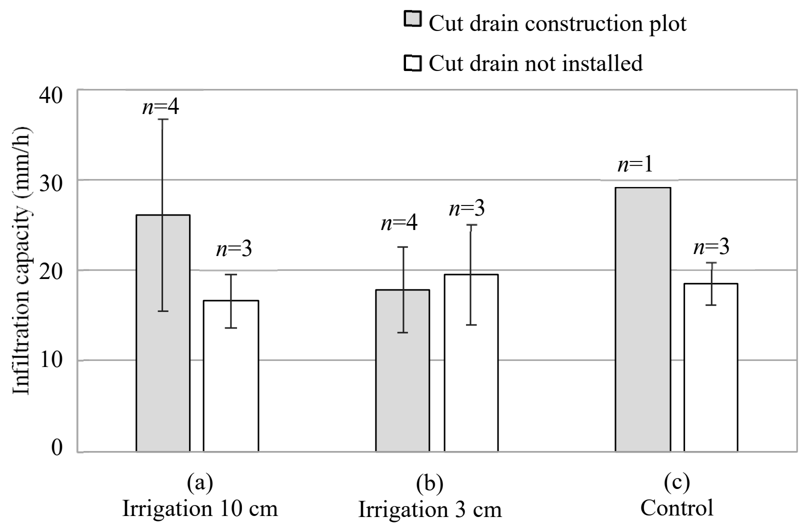
Ten of the experimental plots, being (a) five plots, (b) four and (c) one, showed that no collapse occurred, and irrigated water was retained for more than 4 h with no water leaking into the pits. The relationship between D and t is shown in **Fig. 9**. Calculations showed that the infiltration capacity of plots (a) was 26 mm h^{-1} (average of four plots, with one plot eliminated due to no measurement), that of plots (b) was 18 mm h^{-1} (average of four plots) and that of plots (c) was 29 mm h^{-1} (one plot). The highest capacity was found in plots (c), followed by (a) and (b). However, the order of infiltration capacity was the same and hence there are no significant differences among these values. The infiltration capacities of no Cut-drain construction plots of (a)–(c) were 17-, 19- and 18-mm h^{-1} (average of three plots), respectively. No difference was observed between (a) and respective no Cut-drain construction plots as well as between (b) and respective no Cut-drain construction plots (**Fig. 10**).

Thus, after Cut-drains were constructed, there was no significant difference among infiltration capacities of plots where no water leakage was observed, and therefore it was expected that the capacities were similar in the first 4 h after irrigation to that of the field without Cut-drains.



Note) (a) One point in the irrigation 10 cm is missing due to water leakage at the surface.
Accumulative infiltration volume (D) is the value obtained by subtracting evaporation

Fig. 9 Relationship between infiltration time (t) and accumulative infiltration volume (D)



Note) Error bars are standard deviation
Cut drain construction zone (a) one point of irrigation 10 cm zone is missing

Fig. 10 Infiltration capacity of plots maintained under ponded condition

4.2.5 Evaluation of the method to prevent preferential flow

Before construction of Cut-drains, when irrigation was applied between furrows where the cutting blade passes, the frequency of preferential flow was lower than in the absence of irrigation, and therefore, this method may prevent the sudden entry of leaching water and prevent the collapse of cavities as well as the decrease of a salt leaching effect. In addition, there were no significant differences in soil moisture content between (a) and (b) when Cut-drains were constructed. This indicates that even if system (b) was chosen, if water is limited, or the drainage section area cannot be secured and the amount of irrigation water cannot be well managed, a similar effect could be expected.

5. Conclusion

Constructing Cut-drains in arid and semi-arid areas of Uzbekistan can be challenging because the drilling machine can be lifted when the soil is extremely dry. Therefore, three WCAs in the Syrdarya Region were studied in terms of the soil moisture conditions for which Cut-drains could be constructed during the season when the soil surface was dry. The results showed that the estimated lowest limits of water content were 9–11% in the surface soil layer (0–20 cm) and 12–15% in the 20–40 cm layer. This is a soil moisture limit for the Cut-drain construction below the possible soil plastic limit, and this knowledge could be generalized for other similar construction methods.

The highest limit of water content in the surface soil, however, is based on the soil condition for which tractor operation is ensured, and as for the lower soil layer (60–90 cm depth) it is expected to maintain the soil moisture content at which the constructed cavity will not collapse under its own weight. In the future, we will study the highest limit of water content at which the cavity can be sustained, and the plastic limit will also be studied so that the recommended water content acquired can be quickly and easily applied to farmland with different soil properties.

Cut-drain construction can result in preferential flow from water leaking through the cracks made by the cutting blades as well as through soil pores, if a large amount of water is applied through irrigation and leaching. If a large amount of preferential flow runs into the cavity, the soil wall can be excavated, and the cavity can collapse, which degrades the highly functional water flow of the Cut-drain. The time duration in which leaching water and soil are in contact is also shortened and the salt leaching effect decreases. To prevent the preferential flow that causes problems, a method was studied to irrigate furrow (where the cutting blade passes) beforehand. After construction, a water infiltration experiment was conducted to confirm preferential flow, and this was less frequent than when no irrigation water was applied. It is expected that this method will help prevent some preferential flow.

In the experiment on a method to prevent preferential flow, approximately one week elapsed from when the Cut-drain was constructed until the infiltration experiment was conducted. It is possible that a longer dry period could result in a further lowering of capability to reduce the frequency of preferential flow. In the future, we will study this method at the beginning of the rainy season when tractor operation is not hindered, to evaluate the period for which a better effect could be anticipated.

Acknowledgments

We would like to express our gratitude for assistance from Dr. Sadao Eguchi, Senior Researcher, Institute for Agro-Environmental Sciences, NARO. We gratefully acknowledge, substantial cooperation from the Farmers' Council of Uzbekistan, Scientific Research Institute of Irrigation and Water Problems of the Republic of Uzbekistan (RIIWP), the Hydro-Geological Melioration Expedition (HGME) of the Syrdarya Region and other related organizations. This study was conducted under the research project "Research on Measures against Salinization in Uzbekistan" and was financially supported by the Ministry of Agriculture, Forestry and Fisheries of the Japanese Government.

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*The above article was translated and reprinted from “Irrigation, Drainage and Rural Engineering Journal, Vol. 85, No. 2, pp. II_83-II 90 (2017)”, published by the Japanese Society of Irrigation, Drainage and Rural Engineering.

Characteristics of Salt Leaching in Saline Soil with a Subsurface Hardpan: - A Study Using Undisturbed Soil Core Samples -

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Summary

A comparative leaching experiment of saline soil using undisturbed core samples (20 cm in diameter and 74 cm in length) with and without a hardpan, was carried out following the conventional method of water supply. The samples were collected in salt-affected farmland in the Syrdarya Region of Uzbekistan, with a hardpan formed at a depth of 30 cm. Another sample, without a hardpan, was plowed manually to a depth of 40 cm. A 24-day leaching experiment with total water supply of 300 mm demonstrated clear differences between the two sample types. The amounts of leached water were 98.7 mm for with hardpan and 223.6 mm for without hardpan samples, and the amounts of salt leached from samples were estimated as 276 mg cm^{-2} (discharge ratio: 16.4%) and 597 mg cm^{-2} (35.8%), respectively.

Seventy-two days after the experiment, the saturated hydraulic conductivity of samples without a hardpan at depths of 30–60 cm was reduced to one-200th of that before the experiment. This suggested that hardpans could form not only by tractor compaction but also soil slaking and precipitation of gypsum by leaching operations. It is necessary to develop methods to maintain the effects of breaking the hardpan and confirm their validity through on-site testing.

Keywords

Hardpan, Leaching, Salt-affected soil, Undisturbed soil, Uzbekistan

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1. Introduction

In Uzbekistan, most of the land is arid and semi-arid, but the Amu Darya and Syr Darya Rivers flow on both sides of the country, and irrigated agriculture has long been widely practiced utilizing the water from both rivers, as well as from their branch rivers (Saito, 2015). Large-scale irrigation projects started in the beginning of the 1960s, and irrigated farmland surrounding the Amu Darya and Syr Darya Rivers increased substantially from 1970 over approximately 20 years by 150% and 130%. Drainage facilities were also developed along with these irrigation projects, however, the salinization of farm soil has progressed ever since and agricultural production has been increasingly damaged due to excessive irrigation and inadequate drainage management. According to the Food and Agriculture Organization of the United Nations (FAO), 51% (2.14 million ha) of total irrigated farmland in the country (4.2 million ha) was saline in 1994 (FAO, 2013). In order to maintain sustainable agricultural production in the country, measures and preventive measures against chlorinated soil, which accounts for half of irrigation agricultural land, are required.

In the Syrdarya Region of Uzbekistan, saline groundwater rises to near the surface by capillary action and evaporates, increasing the salinity of the soil. Soil salinization also increases due to the addition of saline irrigation water to agricultural soils (e.g., Shirokova et al., 2000). As a measure to remove salt accumulated in soil, the Hydro-Geological Melioration Expedition (HGME) of the local governmental agency instructs farmers to conduct leaching. In Syrdarya, measures have been taken to supply the amount of leaching water to 2,500-4,500 m^3 ha^{-1} (250-450 mm) depending on the degree of salt damage, and the appropriate starting period is November to December (HGME, 2007). In response to this, farmers cultivate agricultural land to a depth of 20 cm prior to leaching, and then install leaching plots divided into approximately 20 × 20 m, and distribute water for each leaching plot. However, in the field where the drainage function is degraded, in the central of the field away from the drainage channel, and in the vicinity of the service channel, the leaching water is not sufficiently discharged to the outside of the field due to the continuation of the high groundwater level state, and the salinity of the soil remains high (Okuda et al., 2017).

In addition to these factors, salt accumulation due to agricultural engineering is considered to have occurred in Syrdarya. Matsumoto (1988) pointed out that if a hardpan is formed in dry land, stagnant water is temporarily formed above the hardpan, and salt accumulation is likely to occur due to the intense evaporation of the stagnant water. It has been confirmed that a hardpan is formed in a salt-accumulating field in the Syrdarya State immediately below the soil layer about 20 cm from the surface layer, by the impact of compaction due to large-scale tractor driving (Omori and Okuda, 2015). According to Matsumoto (1988), this hardpan under the cultivated soil layer could be one factor facilitating soil salinization.

The purpose of this study was to experimentally verify the assumption that crushing the hardpan promotes the infiltration of leaching water to efficiently leach out the salt of the crop layer and prevent the formation of stagnant water. To achieve this, an indoor leaching experiment was conducted using a soil core in which a hardpan was not disturbed (hereinafter referred to as with hardpan) or was disturbed (hereinafter referred to as without hardpan), and the amount of leaching water, the leaching state of salts, and the chemistry of leaching water were compared. Since it is known that the measured values of lysimeters concerning leaching amounts of nitrogen and salt differ from the actual dynamic observation results in soil with disturbed layer positions and structures (e.g., Ozaki et al., 2001), undisturbed soil was used as the soil core. This is the first leaching experiment using an undisturbed soil core sample of salt soil with a hardpan.

2. Experimental method

2.1 Sampling of undisturbed soil core samples and configuration of experimental equipment

The undisturbed soil was collected from salt-accumulation farmland of the Yangiobad Water Consumers' Association (40°29°N, 68°39°E) located in Syrdarya on September 21–22, 2015. Weeds were removed before soil sampling, and the soil was then cultivated with excavators to a depth of approximately 20 cm so that the condition before leaching could be maximally reproduced. For the soil-core samples of the hardpan fracture, the hardpan was further fractured by cultivation to a depth of approximately 40 cm. For the collection of undisturbed soils, a tool capable of fixing handles to the upper part of a stainless-steel cylinder and having an inner diameter of 20 cm, a thickness 1.0 mm, and a height 100 cm, the tip of which was machined into a saw blade, was used. After inserting the cylindrical body to a depth 80 cm while turning it over manually, or driving it with hammers, soils around the cylindrical body were excavated and the cylindrical body was removed.

Fig. 1 shows an outline of a leaching experiment apparatus using an undisturbed soil core sample. The bottom 6 cm of the collected undisturbed soil was scraped off, a 75-μm nylon mesh was laid on the lower end of the soil, gravel having a particle size of 5 to 10 mm was 3 cm filled, and a support plate (thickness 3 cm) in which a stainless-steel punched plate was processed, was installed (hereinafter referred to as "test piece"). Therefore, the height of the soil column of the test piece was 74 cm. The test piece was installed in a funnel made of stainless steel, and was structured to receive leachate water from the bottom of the test piece into a water sampling container. It was assumed that the leached solution was collected or discharged into the underdrain drainage.

For the leaching experiment, three specimens were prepared for each of the with hardpan and the without hardpan. Dielectric soil moisture sensors (5TE, manufactured by METER) were buried at four depths of 15, 30, 45, and 60 cm from the ground surface, parallel to the ground surface, in each of the with hardpan and the without hardpan specimens. The 5TE sensors were connected to data loggers (Em50, manufactured by METER) and recorded soil moisture and soil EC by depth at 5-minute intervals for one week after leaching water input and at 1-hour intervals thereafter.

The experiment commenced on September 23, 2015, and was terminated when the weight of the leached water became unchanged. In the case of the without hardpan, the leaching was completed with no change in the amount of leached water after 19 days from the start of the test. The test piece of the with hardpan had a constant amount of leached water 72 days after the start of the experiment, and thus the experiment was completed. Daily evaporative emissions in December in winter, when leaching begins in the field, are approximately 0.5 mm (ADB et al., 2008). Due to the room temperature during the experiment being 22 to 24 ˚C and the relative humidity being 37% on average, the surface of the test pieces was covered to prevent evaporation so that the experimental system was as close as possible to resembling the site.

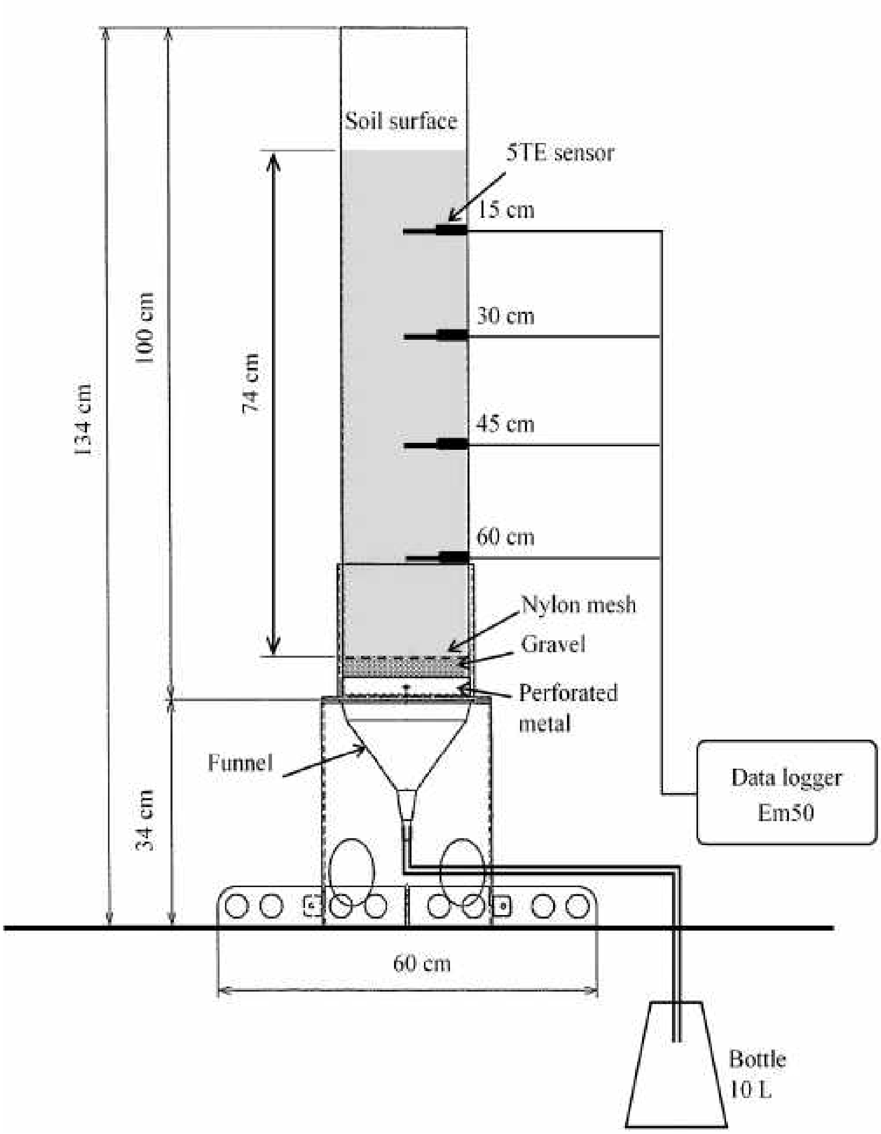

Fig. 1 Outline of a leaching experiment apparatus using an undisturbed soil core sample

2.2 Leaching water

Leaching water used for the experiment was collected from irrigation channels near the soil collection site. Based on the distribution of salt damage on agricultural land (HGME, 2013) in Mirzaabad, Syrdarya, the levels of salt damage on soil-collected agricultural land were classified as moderate (EC_e 4 to 8 dS m^{-1}). Therefore, regarding the amount of leaching water, the standard amount of 3,000 m^3 ha^{-1} (300 mm) (HGME, 2007) at the time of moderate salt damage was used, and the amount of water was 9.2 L, which became the water depth of 300 mm was injected into the upper part of the test piece. At this time, water equivalent to 270 mm was gently supplied so as not to disturb the soil structure, and after the water level at the top of the cylinder dropped to a level of 40 mm, water equivalent to the remaining 30 mm of was supplied. **Table 1** shows the chemical properties of the irrigation water used in the experiments and the amount of salt contained in the water supply of 9.2 L. Total dissolved solids were determined by weighing the evaporation residue in the 50 mL.

Table 1 Chemical properties of the irrigation water used in the experiments

	Concentration ($mmol_c$ L^{-1}, %)	Mass (g) (g L^{-1} × 9.2 L)
Ca^{2+}	8.98 (51.5)	1.66
Mg^{2+}	5.93 (34.0)	0.66
Na^{+}	2.26 (12.9)	0.48
K^{+}	0.28 (1.6)	0.1
Cl^{-}	3.95 (23.3)	1.29
SO_4^{2-}	12.34 (72.9)	5.45
NO_3^{-}	0.05 (0.3)	0.03
HCO_3^{-}	0.59 (3.5)	0.33
EC_w (dS m^{-1})	1.61	-
pH_w	8.21	-
TDS (g L^{-1})	1.13	10.33

TDS: Total dissolved salt

2.3 Measuring item

The soil compactness (Yamanaka method) was measured for the without and the with hardpan in the soil cross section at the sampling point of the undisturbed soil. For soil analyses prior to the initiation of experiments, disturbed soil and undisturbed soil samples were collected from 6 depths of 5, 15, 30, 45, 60 and 80 cm from the ground surface, using a 100 cm^3 cylindrical sampler. The disturbed soil was analyzed for electric conductivity (EC_e) by saturation extraction solution, water-soluble cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), water-soluble anions (SO_4^{2-}, Cl^-, HCO_3^-) and total dissolved solids (TDS) by extracting supernatant solution of soil : water ratio = 1:5, for air-dried fine soil after passing through a 2 mm sieve. The undisturbed soil was subjected to measurement of the volumetric water content, dry bulk density, and saturated hydraulic conductivity (falling head permeability test). The TDS amount of the soil was obtained by multiplying the column volume (cm^3) of each layer collected by the TDS amount (%: g g^{-1}) and dry bulk density (g cm^{-3}) of the dry soil 1 g, and adding the TDS amount obtained for each layer. At this time, the soil column height of 74 cm was evenly divided into 15 parts, and the TDS quantity and dry density between the measured points were obtained by interpolating the TDS quantity and dry bulk density by the spline method.

Twenty-four days after initiation of the study, and approximately the same period as the leaching flood period in the field, the volume of leached water was measured, and the chemical properties of the permeated water were analyzed using the internal 60 mL of the leached water. In order to measure the chemical and physical properties of the soil after completion of the experiments, undisturbed soil samples and disturbed soil samples were collected from a single sample of the with hardpan samples and the without hardpan at a depth of 5, 15, 30, 45, 60, and 71 cm using a 100 cm^3 cylindrical sampler with a height of 5 cm.

For the values of soil moisture and soil EC obtained from the 5TE sensor, the calibration results of Omori (2018) was applied, and the volume moisture content (θ, m^3 m^{-3}) and soil EC_e (hereinafter referred to as $EC_{(c)}$, dS m^{-1}) were estimated. This method combines the method of soil moisture analysis by Inoue et al. (2016) and the method of soil salinity analysis by Rhoades et al. (1976) to obtain the numerical solution of the volume moisture content by the two-fraction method.

The estimation equation of θ is expressed by the logarithmic equation of the equation (1) when the EC (EC_p) of the soil solution is used as a coefficient after plotting the experimentally obtained θ and the square root ($\varepsilon_a^{0.5}$) of the dielectric constant which is the sensor output value at that time.

$$\theta = (a_1\, EC_p^2 + b_1\, EC_p + c_1)\times\ln(\varepsilon_a^{0.5}) + (a_2\, EC_p^2 + b_2\, EC_p + c_2) \quad (1)$$

where, a_1, b_1, c_1, a_2, b_2, and c_2 are experimental constants.

The Rhoades model is a model for estimating EC_p from measurements of apparent soil EC (EC_a) at any θ, and is represented by equation (2).

$$EC_p = \frac{EC_a - EC_s}{\theta\,(a\theta + b)} \quad (2)$$

where, EC_s is the electric conductivity of the solid phase (dS m^{-1}), and 0.19 dS m^{-1} was obtained from the calibration test. a and b are experimental constants.

Table 2 shows the experimental constants of Eq. (1) and (2). By substituting Eq. (2) into Eq. (1), sensor output values EC_a and ε_a and the experimental constant values shown in **Table 2** are used, and only θ becomes an unknown formula. Since it is difficult to solve this equation algebraically with respect to θ, a numerical solution was obtained using the bisection method. The obtained value of θ was substituted into Eq. (2) to obtain EC_p.

Table 2 Experimental constants of Eq. (1) and (2)

Eq. (1)						Eq. (2)	
a_1	b_1	c_1	a_2	b_2	c_2	a	b
2.05×10^{-4}	−0.0133	0.4354	-1.70×10^{-4}	0.00893	−0.2132	1.1897	0.0079

$EC_{(c)}$ was obtained by the following equation (3).

$$EC_{(c)} = \frac{EC_p \, \theta}{\left(1 - \frac{\rho_d}{\rho_s}\right)} \qquad (3)$$

where, ρ_d is the dry bulk density (g cm^{-3}) and ρ_s is the soil particle density (g cm^{-3}).

3. Results and discussion

3.1 Soil physics and chemical properties before experiment

Fig. 2 shows the vertical distributions of the without hardpan and the with hardpan soil compactness, volumetric water content, dry bulk density, and saturated hydraulic conductivity in the initial soil at the undisturbed soil sampling point, respectively.

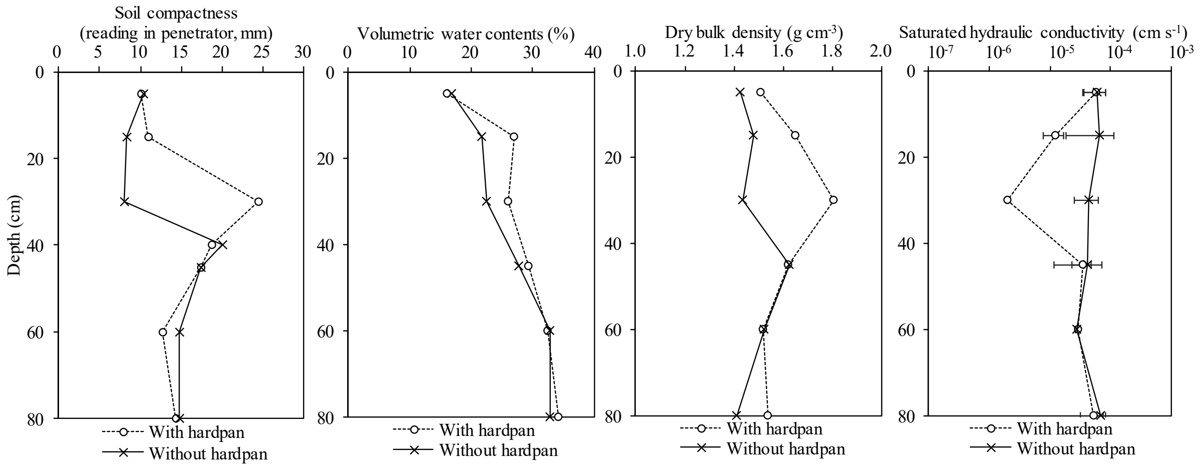

Fig. 2 Soil physics in the initial soil

(Soil compactness, Volumetric water content, Dry bulk density, and Saturated hydraulic conductivity)

From the soil profile survey, the hardpan was formed under the crop layer, and a white mottle was confirmed at the depths of 30 to 50 cm. Such a mottle was also observed in the surrounding area, and it was inferred that calcium carbonate and calcium sulfate were precipitated.

From the results of soil compactness, dry bulk density, and saturated hydraulic conductivity, it was confirmed that the hardpans were formed at the depth of 30 cm. The saturated hydraulic conductivities of the with hardpan at depths of 30 cm and 45 cm were 1.98×10^{-6} cm s^{-1} and 3.53×10^{-5} cm s^{-1}, respectively. The saturated hydraulic conductivities of the without hardpan at the same depth were 4.40×10^{-5} cm s^{-1} and 4.24×10^{-5} cm s^{-1}, respectively. Since the crushing of the hardpan was up to approximately 40 cm in depth, the soil physics at a depth of below 45 cm differed less, depending on whether or not the hardpan was crushed, and the soil physics were almost the same condition.

Table 3 shows the particle size composition and the soil particle density in the soil cross-section of the without hardpan and the with hardpan. They were divided into a layer position (5, 10, and 30 cm) shallower than the hardpan and a depth (50 and 80 cm) deeper than the hardpan. According to the International Society of Soil Sciences method, the soil property was clay loam soil (CL), regardless of the depth of the without hardpan and the with hardpan. For sand, the percentage of fine sand (0.2–0.02 mm) was very high at all depths, and the percentage of coarse sand (0.2–2.0 mm) was as low as 0.1–0.3%. The dry bulk density, soil compactness, and saturated hydraulic conductivity tended to be characteristic at the depth of 30 cm, but it was confirmed that there was no change in the layer position in the soil property.

Table 3 Particle size composition and the soil particle density in the soil

Depth (cm)	Texture	Clay	Silt	Sand		Particle density ($g\ cm^{-3}$)
				Fine	Coarse	
		(%)				
[With hardpan]						
5, 10, 30	Clay loam	21.7	25.6	52.5	0.2	2.74
50, 80	Clay loam	19.2	28.1	52.6	0.1	2.81
[Without hardpan]						
5, 10, 30	Clay loam	22.1	26.2	51.4	0.3	2.74
50, 80	Clay loam	19.5	27.3	53.0	0.2	2.78

Fig. 3 shows the vertical distribution of the water-soluble ions by extracting supernatant solution of soil, water ratio = 1:5, in the initial soil with hardpan and without hardpan. Both conditions showed high salt concentrations at 5 cm depth, indicating that salts accumulated near the ground surface due to soil-surface evaporation. The composition of water-soluble cations was 48.3% and 42.5% for Ca^{2+} and 72.6% and 71.2% for SO_4^{2-}, respectively, for the with hardpan and the without hardpans, respectively. The total amount of water-soluble cations per dry soil amount of the without hardpan was approximately 1.18 times higher on the whole layer average than that of the with hardpan, and in particular, Na^+ was 1.50 times higher than that of the with hardpan. This difference is due to the heterogeneity of soil salinity in the field.

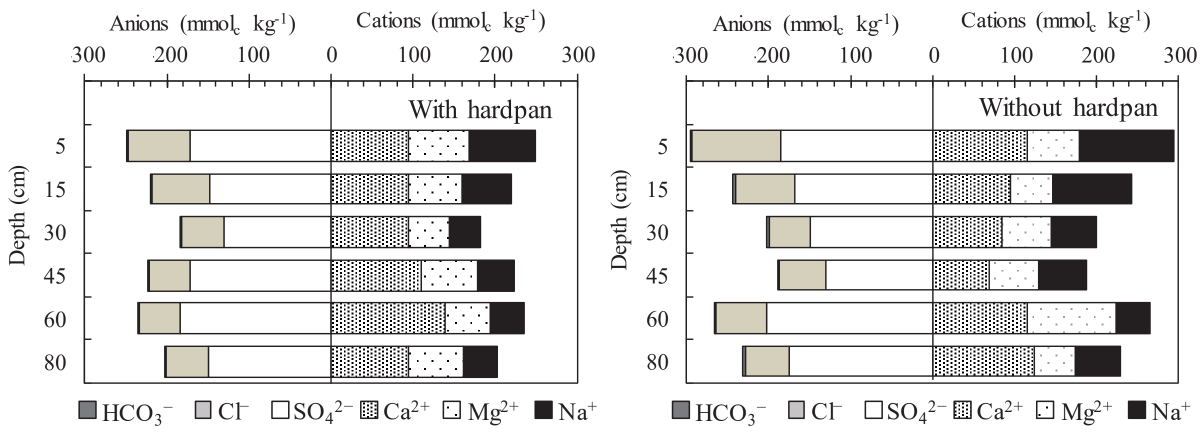

Fig. 3 Vertical distribution of the water-soluble ions in the initial soil

3.2 Amount of leachate and chemistry of leachate after 24 days

Fig. 4 shows the amount of the with hardpan and the without hardpan discharged water volume 24 days after the start of the experiment, and **Fig. 5** indicates the amount of ions (g) obtained by multiplying the measured value of the water-soluble ion concentration of the discharged water volume by the amount of leachate. In the test pieces of with hardpan, the supplied water still remained about approximately 110 mm from the top of the soil surface.

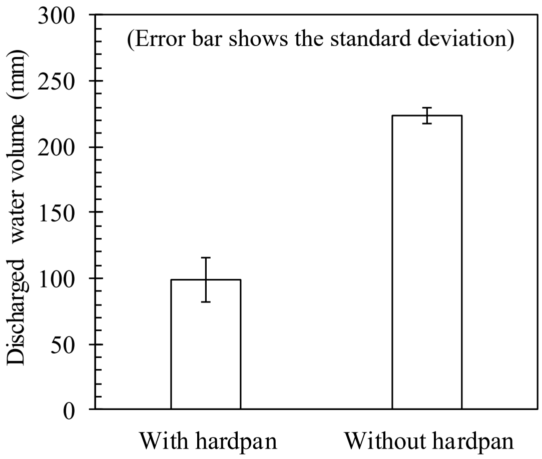

Fig. 4 Comparison of discharged volume after 24 days

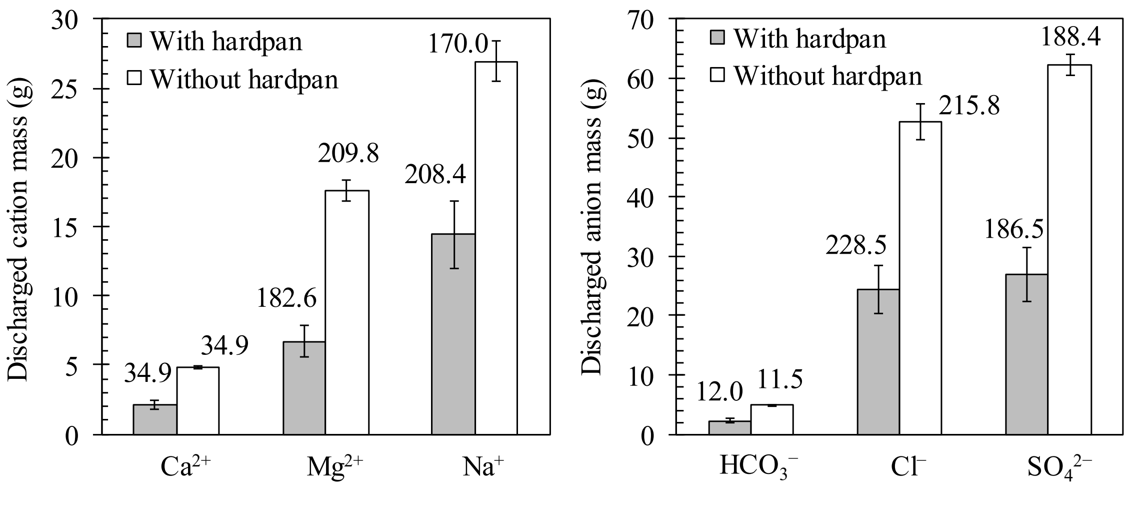

Fig. 5 Ionic content and concentration of discharge after 24 days
(The figure shows the ion concentration $mmol_c\ L^{-1}$ and the error bar shows the standard deviation.)

As a result of the leaching experiment at 24 days from the beginning of the experiment, the discharged water amount was 98.7 mm (32.9%) for the with hardpan and 223.6 mm (74.5%) for the without hardpan with respect to the supply water amount of 300 mm. Daily units of the saturated hydraulic conductivity correspond to mean 4.1 mm d^{-1} (4.75×10^{-6} cm s^{-1}) for the with hardpan, 9.3 mm d^{-1} (1.08×10^{-5} cm s^{-1}) for the without hardpan. In addition, the EC_w of the discharged water was approximately the same as 32.2 and 31.6 dS m^{-1} in the with hardpan and without hardpan, respectively.

The chemical equilibrium model Visual MINTEQ ver. 3.0 (Gustafsson, 2012) was used to estimate the salts dissolved or precipitated during the leaching experiments. Both the without hardpan and the with hardpan were presumed to be predominantly free ions of Na^+ and Cl^- in the discharged water, followed by sulfate species of $MgSO_4$ (aq) and $NaSO_4^-$. The salt mineral species that precipitated was estimated as dolomite ($CaMg(CO_3)_2$).

According to **Fig. 5**, discharged salts were eluted with water-soluble cations in the order of Ca^{2+}<Mg^{2+}<Na^+, and with water-soluble anions in the order of HCO_3^-<Cl^-<SO_4^{2-} in both the without hardpan and the with hardpan. The TDS amount of the discharged water was estimated to be 276 mg cm^{-2} for with hardpan and 597 mg cm^{-2} for without hardpan per unit area of the test piece, and the TDS amount of the discharged water was estimated to be 84.3 g for the with hardpan and 182.1 g for the without hardpan. It was confirmed that 2.2-times salt was eluted by crushing the hardpan.

Assuming that the water-soluble cation compositions in the test specimens were equivalent to those in the initial soils prior to the beginning of the experiment, the average Ca^{2+} concentrations in the whole layer were 105, 101 $mmol_c$ kg-soil $^{-1}$, 63, 65 $mmol_c$ kg-soil $^{-1}$, and 51, 71 $mmol_c$ kg-soil $^{-1}$ in the with hardpan and without hardpan, respectively, in order of Mg^{2+}, and Na^+<Ca^{2+}. However, the amount of Ca^{2+} in the discharged water was small, resulting in preferential discharging of Mg^{2+} and Na^+.

3.3 Physics and chemistry of the test pieces after completion of the experiment

The test piece of the without hardpan had no change in the amount of discharged water 72 days after the start of the experiment, and thus the experiment was completed. The discharged water amount of the with hardpan became 222.0 mm and was 1.6 mm, 46 mL smaller than the discharged water amount of the without hardpan in which leaching was previously completed.

3.3.1 Soil physical property

Fig. 6 shows the vertical distributions of the volumetric water content, dry bulk density, and saturated hydraulic conductivity taken for each layer position from one test piece of the with hardpan and one test piece of the without hardpan after completion of the experiment. The water content by volume of both test pieces ranged from 34.1 to 37.3% in depth from 5 to 45 cm, and from 40.5 to 41.3% in depth from 60 to 74 cm. The volumetric water content of both test pieces was the same as the saturated volumetric water content of about 41% in depth from 60 to 74 cm. The dry bulk density and saturated hydraulic conductivity profiles tended to be almost the same for both test pieces. The saturated hydraulic conductivity of the without hardpan declined to approximately one-200 times compared to the initial state at 30 cm and 45 cm depths of 2.11×10^{-7} cm s^{-1}, 1.77×10^{-6} cm s^{-1}, respectively, and returned to the same state as with hardpan. The cause of this is considered to be as follows: After the water supply, the subsidence of the ground surface at the time when the flooded condition disappeared was 3 cm in the without hardpan, and 1 cm in the with hardpan. The amount of sedimentation remained unchanged after the end of the experiment. Therefore, it was presumed that when leaching water was supplied, the air in the interstices of the soil was compressed by the infiltration of water, the bonds between the clay mineral particles were weakened by the pressure, and the water permeability was lowered by increasing the density of the soil (slaking phenomenon). A simple test was carried out to confirm the slaking property of salt soil in the field, and when a naturally dried soil mass was immersed in water, slaking started instantaneously, and the soil was rapidly shredded and muddy (**Fig. 7**). Local geology consists of tertiary mudstones (Morozov, 2014), which are generally highly slaking and swelling. After completion of the experiments, soils of 30 to 60 cm in depth had less voids and became denser (**Fig. 8**), and white patches of calcium carbonate and calcium sulfate were observed (**Fig. 9**).

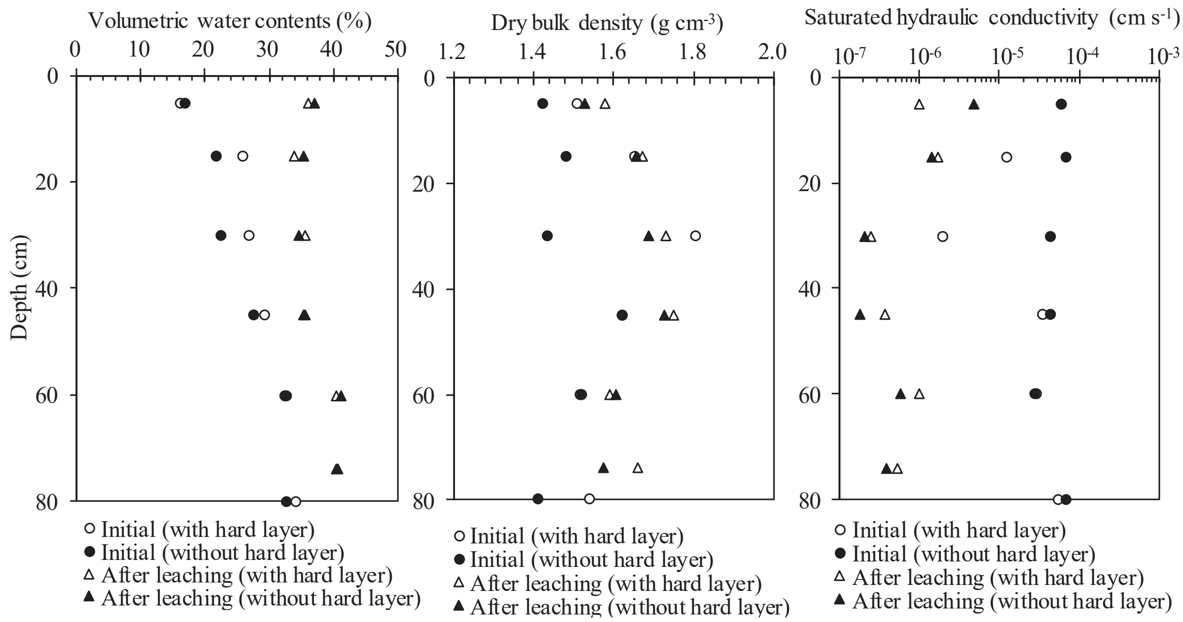

Fig. 6 Soil physics after completion of the experiment

Volumetric water content, Dry bulk density, and Saturated hydraulic conductivity

Fig. 7 Slaking test. Left, before flooding and right, after 5 minutes

15 cm in depth   Left: 30 cm in depth, right 60 cm in depth

Fig. 8 Soil samples after leaching experiment (disturbed hardpan, after drying)

15 cm in depth   Top: 60 cm in depth, bottom 30 cm in depth

Fig. 9 Soil samples after leaching experiment (broken soil cores of Fig. 8)

3.3.2 Soil chemistry

Fig. 10 shows vertical distributions of water-soluble ions of the with hardpan and the without hardpan at the end of the experiment. When the relationship between EC_e and the sum of cation concentration at each layer measured before and after the experiment was obtained, a clear linear relationship was obtained as follows:

$$\text{Total cations (mmol}_c\text{ kg}^{-1}) = 10.663 \times EC_e \qquad (r^2=0.93) \tag{4}$$

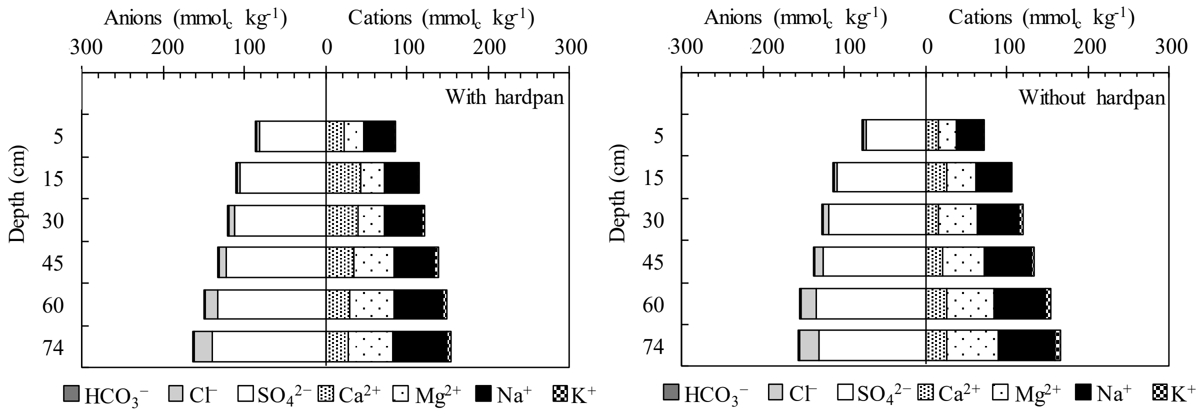

Fig. 10 Vertical distribution of the water-soluble ions after completion of the experiment

Table 4 shows the salt balance at the start of the experiment, 24 days after the start of the experiment, and 72 days after the end of the experiment in terms of the TDS amount and each ion amount. The amount of each ion in the soil at the beginning of the experiment was calculated by multiplying the column volume (cm^3) of each layer collected by the amount of each ion in the dry soil 1 g (%: g g^{-1}) and the dry bulk density (g cm^{-3}), and then summing the ion amounts of each layer for each ion, similar to the method of calculating the amount of TDS in the specimen. The ratio of the total of major ions such as Ca^{2+} to the TDS content of leachate at 24 and 72 days after the start of the experiment was an average of 0.908 (calculated from the values marked with * in **Table 4**). This difference was estimated to be the sum of undissociated components (e.g., H_4SiO_4) and trace components not detected by water-soluble ion analysis, and the major ions in the soil were also considered to have approximately the same ratio to TDS content. This ratio was multiplied by each ion amount to calculate the ion amount of the soil. The TDS and ion content of the soil after 24 and 72 days were determined by subtracting the measured values in the leachate after 72 days from the start of the experiment. The amounts of TDS in the test pieces prior to the start of leaching were estimated to be 505.2 g in the with hardpan and 497.9 g in the without hardpan. It was inferred that the TDS amount was calculated to be small in the test pieces of the hardpan crushing due to the impact that the dry bulk density became low at the time of the hardpan disturbance.

Table 4 Mass balance of TDS amount and each ion amount in leaching experiment

	Initial			Period (days)						
				24			72			
	Existing salts in soil	Salts in water supplied	Total (a)	Drained salts (b)	Remained salts in soil (a)−(b)	(%) (b)/(a)	Drained salts (c)	Remained salts in soil (a)−(c)	(%) (c)/(a)	Total
[With hardpan]										
Ca^{2+}	71.7	1.7	73.4	2.1	71.3	(2.9)	5.7	67.7	(7.8)	73.4
Mg^{2+}	24.4	0.7	25.1	6.7	18.4	(26.7)	16.9	8.2	(67.3)	25.1
Na^{+}	42.9	0.5	43.4	14.4	29.0	(33.2)	24.5	18.9	(56.5)	43.4
HCO_3^{-}	3.5	0.3	3.8	2.2	1.6	(57.9)	2.8	1.0	(73.7)	3.8
Cl^{-}	67.4	1.3	68.7	24.4	44.3	(35.5)	48.8	19.9	(71.0)	68.7
SO_4^{2-}	254.1	5.5	259.6	26.9	232.7	(10.4)	62.3	197.3	(24.0)	259.6
Total	464.0	10.0	474.0	*76.7	397.3	(16.2)	*161.0	313.0	(34.0)	474.0
TDS	505.2	10.3	515.5	*84.3	431.2	(16.4)	*179.9	335.6	(34.9)	515.5
[Without hardpan]										
Ca^{2+}	59.2	1.7	60.9	4.8	56.1	(7.9)	4.8	56.1	(7.9)	60.9
Mg^{2+}	26.1	0.7	26.8	17.4	9.4	(64.9)	17.4	9.4	(64.9)	26.8
Na^{+}	47.9	0.5	48.4	26.6	21.8	(55.0)	26.6	21.8	(55.0)	48.4
HCO_3^{-}	5.3	0.3	5.6	4.8	0.8	(85.7)	4.8	0.8	(85.7)	5.6
Cl^{-}	71.7	1.3	73.0	52.1	20.9	(71.4)	52.1	20.9	(71.4)	73.0
SO_4^{2-}	245.7	5.5	251.2	61.7	189.5	(24.6)	61.7	189.5	(24.6)	251.2
Total	455.9	10	465.9	*167.4	298.5	(35.9)	167.4	298.5	(35.9)	465.9
TDS	497.9	10.3	508.2	*182.1	326.1	(35.8)	182.1	326.1	(35.8)	508.2

Fig. 11 shows the leaching ratios of Mg^{2+} and Na^{+} at each soil layer. The negative range represents an increase in concentration over that found before the experiment. From the calculation of the balance, the Na^{+} leaching rate of the with hardpan after 72 days was calculated to be 56.5%. However, Na^{+} was hardly leached below 30 cm depth. In the water supply 300 mm, Na^{+} elutes directly above the hardpan, and moves and accumulates in the lower layer as the leaching water permeates. It was confirmed that even if the hardpan was disturbed, it could not leach deeper than 60 cm, and it accumulated in the lower layer.

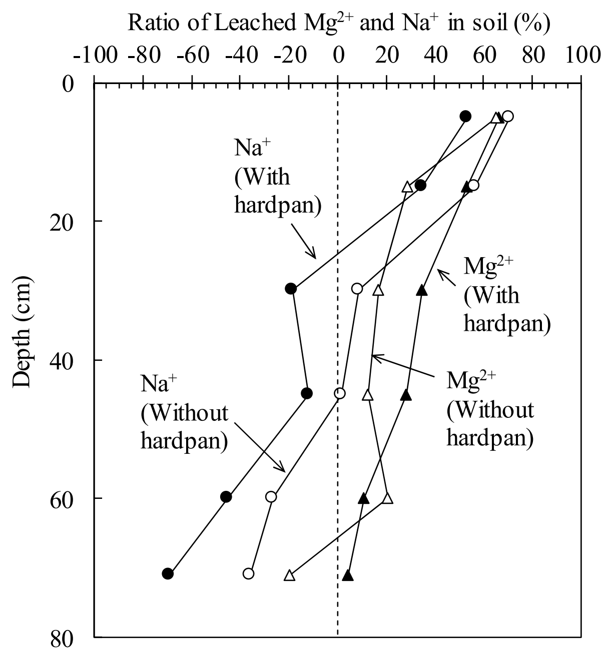

Fig. 11 Leaching ratio of Mg^{2+} and Na^{+} at each soil layer

Focusing on the calcium content of the soil at the start of the experiment and after 72 days, it was suggested that the estimated calcium content in the test pieces of the with hardpan were 71.7 g (at the start of the experiment) and 67.7 g (after 72 days), and in the test pieces of without hardpan were 59.2 g (at the start of the experiment) and 56.1 g (after 72 days) and that Ca^{2+} remained in the soil even after the experiment (**Table 4**). However, the water-soluble Ca^{2+} concentration after 72 days was reduced by approximately 70% compared with before the experiment (Fig. 10). With regards to this discrepancy, dissolved species and salt mineral species in soils before and after experiments were confirmed by Visual MINTEQ. The results of **Fig. 3** and **Fig. 10** were used for the ion concentration for comparison by layer position. The salt minerals in the soils prior to the experiments were estimated to be dolomite, gypsum ($CaSO_4 \cdot 2H_2O$), calcite ($CaCO_3$), and gypsum after 72 days. **Fig. 12** shows the ratio of free ions Ca^{2+} and SO_4^{2-} to total dissolved species concentrations. The percentage of free Ca^{2+} was at maximum approximately 6%. The larger percentage of free Ca^{2+} in the pre-experiment of the without hardpan at the depth of the 45 cm compared with the with hardpan was considered to be the impact of the without hardpan. In addition to Ca^{2+}, water-soluble calcium was present in forms such as $CaSO_4$ (aq), $CaCl^{+}$, $CaHCO_3^{+}$, and $CaCO_3$ (aq). For free SO_4^{2-}, both the with hardpan and the without hardpan increased after the experiments. Apart from the addition of the SO_4^{2-} of the supplied water, it was inferred that the gypsum present in the soils was dissolved and increased.

VAN Hoorn et al. (1997) showed that, in leaching experiments using lysimeters, the calcium content in soil was almost the same for two years due to the aging dissolution of gypsum in clay soil (CL), and the carbonates of calcium and magnesium were discharged, which was similar to the experimental results. In the leaching process of calcium in this study, highly soluble $CaCl_2$ and similar are discharged, and the water-soluble calcium concentrations in soils are lowered. Conversely, although the gypsum in the soil was dissolved by the water supply, it was inferred that the gypsum was produced and precipitated when the water supply required for the dissolution disappeared, and the poorly soluble calcium salt remained.

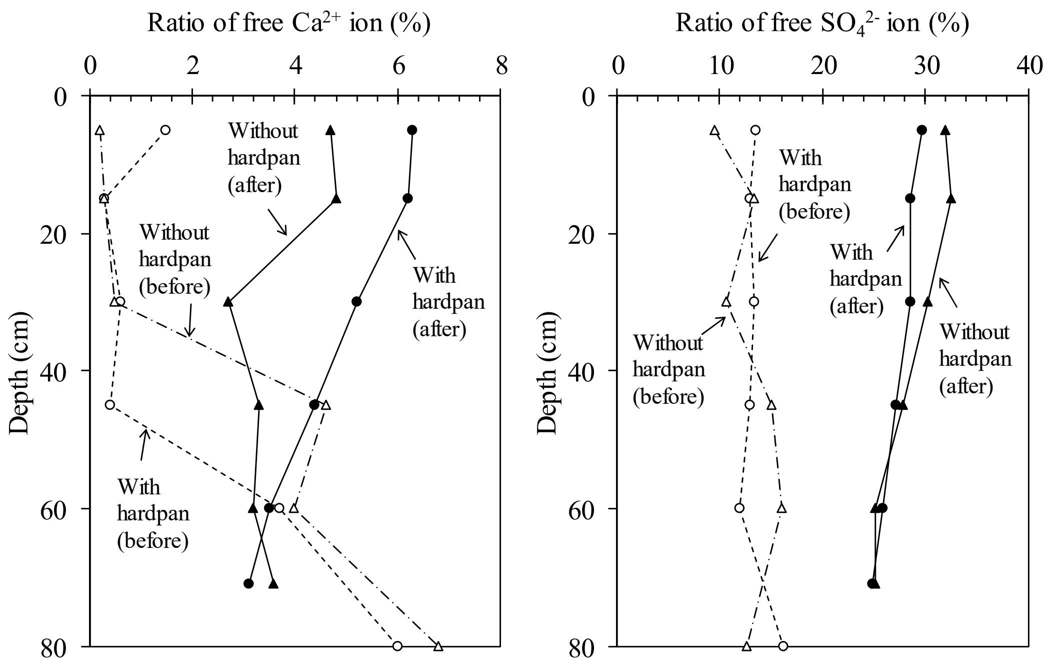

Fig. 12 Changes in free Ca^{2+} and SO_4^{2-} ratios at various depths before and after the leaching experiment

3.3.3 Changes in soil salinity by layer level

Fig. 13 and **Fig. 14** show the changes in $EC_{(c)}$ during leaching process with 5TE sensor installed in each of the with hardpan and the without hardpan. **Fig. 13** shows from the start of the experiment to the end of leaching, and **Fig. 14** represents the start of the experiment to 3 hours. As shown in **Fig. 14**, prior to the beginning of the experiment, the soil EC_e ($EC_{(c)}$) obtained by the 5TE sensors at the 15 cm depth showed 10 dS m^{-1} for both specimens. The $EC_{(c)}$ at 15 cm depth measured prior to the initiation of the experiments were 19.6 and 21.6 dS m^{-1} for the with hardpan and without hardpan, respectively. The differences between the sensor values and the measured values are due to the presence of air gaps between the sensor and the soil because the soil was cultivated to a depth of approximately 20 cm. After the leaching water reached the depth of 15 cm 10 minutes after the start of the experiment, the sensor values rose to 50 dS m^{-1}. Considering that the soil EC_e at the 5 cm depth was 24.5 and 28.1 dS m^{-1} in the with hardpan and without hardpan, respectively, it was considered that the salt contained from the surface layer to the 15 cm depth was dissolved by the leaching water. With regards to the depth beyond the soil crop layer, when the hardpan was not disturbed, the lower $EC_{(c)}$ decreased slowly at the 30 cm depth of the hardpan (**Fig. 13**). If the time at which $EC_{(c)}$ started to decrease was defined as the leaching initiation time, as shown in **Fig. 13**, leaching started after one day in the without hardpan at 30 cm depth, after three days in the without hardpan at 30 cm depth, after five days in the without hardpan at 60 cm depth, and after 26 days in the without hardpan at 60 cm depth. The test piece of the with hardpan took 72 days to lower to the EC value discharged in 19 days in the without hardpan. In the case of without hardpan, salts in the test pieces were quickly removed with the infiltration of leaching water.

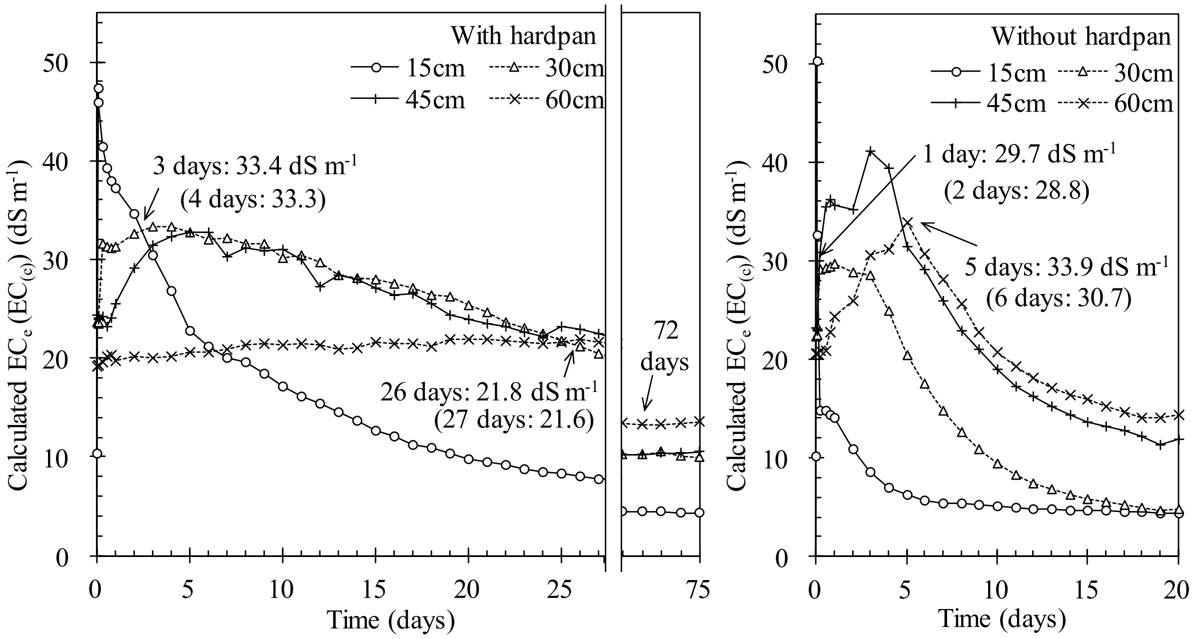

Fig. 13 Changes in $EC_{(c)}$ during leaching process with 5TE sensor.
(Left, with hardpan, and right, without hardpan.)

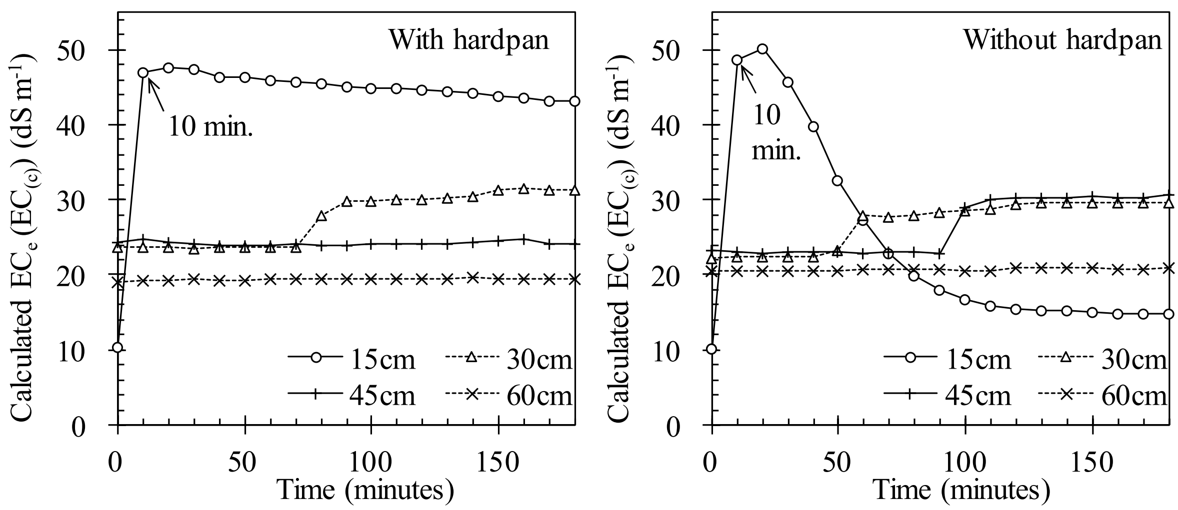

Fig. 14 Changes in $EC_{(c)}$ up to 3 hours after leaching experiment.
(Left, with hardpan, and right, without hardpan.)

3.4 Comparison between leaching experiments and on-site conditions

From the results of this experiment, it was confirmed that the supplied water quickly permeated downward by the without hardpan, and the salt content in the soil was leached out. Conversely, even if the hardpan was formed, all of the supplied water was leached after 72 days, and the desalting effect was the same as that of the without hardpan. However, in the actual field, the leaching operation is approximately 14 to 24 days, and does not require a long period as shown in the present experimental result. From this, it was considered that the supplied water was desalted to a level shallower than the hardpan and flowed out in a horizontal direction, or permeated downward by selecting a place with good partial water permeability.

4. Conclusion and Recommendations

Based on the results of this experiment, it was indicated that the formation of the hardpan lowered the soil physics not only by the tractor compaction but also by combined factors such as the slaking phenomenon and gypsum formation in the leaching process, accompanied by winter leaching operation. In addition, it was confirmed that the effect of the without hardpan was lost by a one-time leaching operation.

In these experiments, the soils were relatively finely loosened up to the depth 40 cm by using excavators for hardpan disturbing. It was also concluded that this caused a water permeability reduction of 30 to 60 cm in depth. Some farmers own a subsoil breaker (subsoiler, three to four crushing claws, depth 60 cm), but in the actual field, it seems to be a practical method to roughly crush the hardpan by the subsoil breaker. Subsoil breaking is often combined with underdrain drainage (Uchiyama, 1983).

As a counter measure based on the experimental results, we concluded that, in the case of the quantity of 300 mm for leaching operation, the method of hardpan crushing to approximately 40 cm depth in advance and preparing shallow underdrain water to approximately 60 to 70 cm depth was effective for quickly infiltrating the leaching water downward, and the method of discharging the salt washed out by the leaching to the open-channel drainage which was prepared around the agricultural land. In the future, it will be necessary to examine the method of sustaining the effect of the without hardpan, and to verify it through field tests and other research.

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*The above article was translated and reprinted from “Sand Dune Research, Vol. 66, No. 1, pp. 9-20 (2019)”, published by the Japanese Society of Sand Dune Research.

Salt Removal Technology by Shallow Subsurface Drainage in Combination with a Cut-drain

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Summary

In Uzbekistan, secondary salinization of irrigated lands is caused by rising groundwater level due to excessive irrigation and drainage system malfunction. Countermeasures such as drainage system maintenance, drainage facility construction, and leaching opration have been adopted to control salinity. However, there are still fields where salinity levels remain high because of incomplete dredging operations, reduced deep subsurface drainage system discharge capacity, or ineffective approaches to vertical drainage operations. To achieve stable production and crop diversification, prompt salt removal is necessary. Thus, we proposed a shallow subsurface drainage technology to ensure effective salt removal from the surface soil layer. The technology was studied in combination with a new drain drilling technique (Cut-drain) developed in Japan. It was experimentally introduced in farmers' fields in the Syrdarya Region. A leaching test performed in the study field revealed that highly saline water was observed at the outlet of the drainage pipe. The results of our study showed an approximately 20% increase in cotton yield, along with a decreasing salinity trend in the surface soil layer. Our study demonstrated that this technology can be employed as an effective measure for controlling salinity in a field.

Key words
Salinization, Drainage, Subsurface drainage, Cut-drain

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1. Introduction

In Uzbekistan, secondary salinization of irrigated lands has been caused by rising groundwater table due to excessive irrigation and drainage system malfunction. The current drainage system has been deteriorating since the 1990s, after the dissolution of the Soviet Union. The system is mainly composed of open channel, subsurface, and vertical drainage. To improve irrigated land, the government of Uzbekistan started a special fund to repair and replace these aging systems, resulting in satisfactory conditions in some areas. However, there are areas where the drainage systems are in disrepair (Frenken, ed., 2013). Incomplete dredging operations and inadequate open drainage maintenance have caused an increase in the drainage water level. Under such drainage conditions, some deep subsurface drainage outlets have been blocked by soil or submerged in the drainage water, leading to poor groundwater discharge under the field. Currently, the performance of vertical drainage systems has been lower compared to their performance at the time of original construction. We revealed that vertical drainage could not sufficiently control the groundwater level because of a shortage and inappropriate timing of operations (Okuda et al., 2015a). In fields with a malfunctioned drainage system, to achieve stable agricultural production and well adapt the field to crop diversification, prompt and steady salt removal technology is required. Regarding prompt salt removal, a study indicated that shallow subsurface drainage (main drainage depth: 70 cm) was an effective method to discharge infiltrated water with salt (Chiba et al., 2012).

Thus, we proposed a shallow subsurface drainage technology to effectively remove salt from the field. In general, shallow subsurface drainage requires high drain pipe density (pipe length per unit area), which increases construction costs. Therefore, this technology was studied in combination with a "Cut-drain" as a low-cost alternative. A Cut-drain is constructed by a new drain drilling machine developed in Japan. This was the first trial to apply Cut-drains in a semi-arid area for the removal of salt using shallow subsurface drainage. The experimental study was conducted on farmers' fields in the Syrdarya Region, the Republic of Uzbekistan. In this paper, we report experimental field results using shallow subsurface drainage technology with Cut-drain.

2. Materials and methods

2.1 Study area

The study area is shown in **Fig. 1**. Desert and steppe regions occupy 60% of Uzbekistan and are located in the western area of the country. The eastern area connects to the Tian Shan mountains and Pamir plateau. The country is sandwiched between the Amu-Darya and Syr-Darya rivers, both of which flow to the Aral. The weather is a continental climate. It is characterized by drastic temperature changes, with hot and dry summers and cold and wet winters. Annual precipitation ranges from 100–250 mm in the desert region, 200–545 mm at the foot of mountains or plain areas, and 400 mm and over in mountain areas (Makhmudov, 2006). The Syrdarya Region is located to the east of the steppe region, which is a plain area. The aridity index is 0.32, and the average precipitation over the last five years is 335 mm.

It is classified as a semi-arid region. The temperature sometimes exceeds 40 °C in the summer and below −10 °C in the winter. Precipitation is mainly observed from October, end of autumn, to April, beginning of spring.

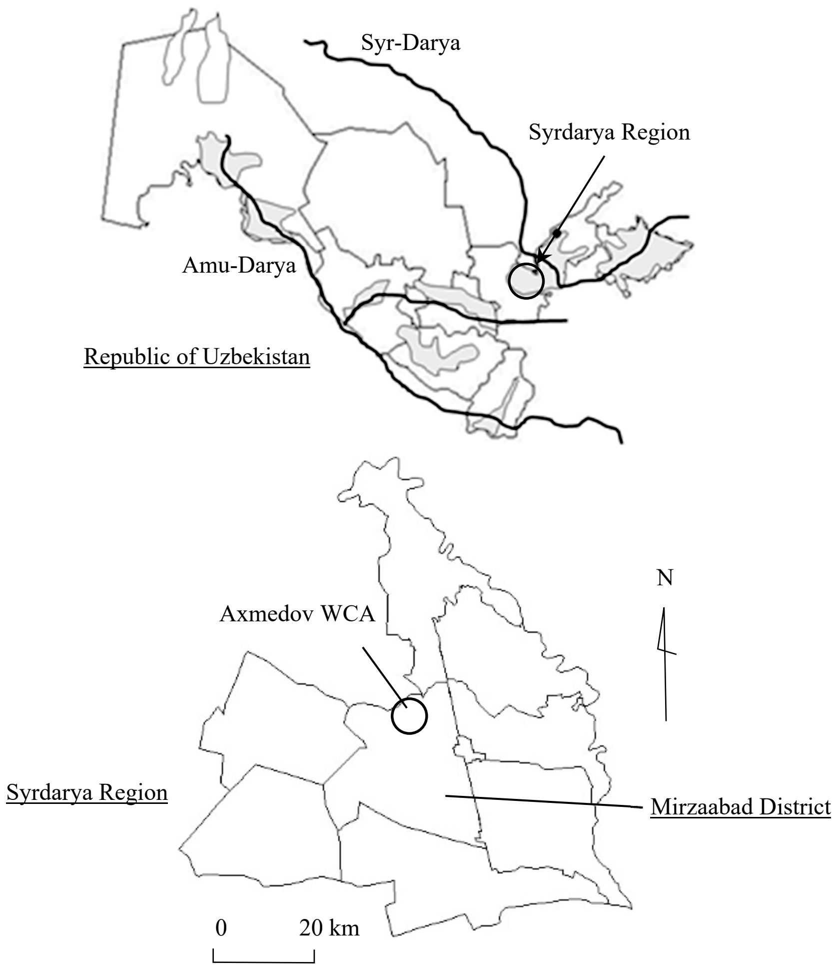


Fig. 1 Location map of research sites

According to the Farmers' Council of Uzbekistan data, the country had 4.3 million ha of irrigated land in 2014. Currently, 47% of this land is affected by salinization (the electric conductivity of the saturation extract of the soil, EC_e > 2 dS m^{-1}). In particular, salinization is spreading over 98% (280 thousand ha) of the irrigated land in Syrdarya Region.

This study was conducted on actual farmlands in a Water Consumers' Association (WCA) of Axmedov at Mirzaabad District where the salinity level is the most serious in the Region (**Fig. 2**). The name of the farm studied is "Nozima Durdona Fayz," which covers around 30 ha.

Regarding the drainage condition, the farm adjoins open drainages. According to the topographical survey near the field, the difference of elevation between the drainage bottom and the lower field is approximately 2.0–2.5 m. During the winter season, the drainage water level rises by 0.5–1.0 m, resulting in an elevation difference of 1.0–2.0 m. The resulting hydraulic gradient from the field to open drainage becomes quite small (Kitamura et al., 2006).

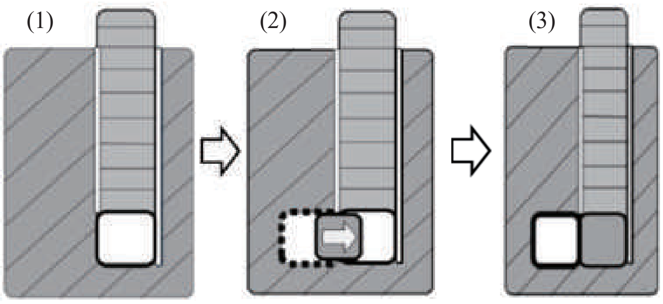
Fig. 2 Educed salt in wheat field (January 2, 2016 in Axmedov WCA)

2.2 Experimental field

A new shallow subsurface drainage system should be low-cost to disseminate widely among farmers. Therefore, this study used such a system in combination with a Cut-drain in actual farmers' fields.

Cut-drain construction has a unique drilling method. The drilling machine has two long blades and a side-cutter in the lower part. The blades are inserted into the soil, cutting a soil column of 10 cm width and raising it by 10 cm. The side-cutter simultaneously cuts a square-shaped section of soil from the side of the newly created space and slides this soil into the space formed by the risen soil block (Okuda et al., 2015b). The new cavity acts as a relatively stable mole drain (**Fig. 3**). The drilling machine is towed by a tractor (130–140 HP) to make a conduit under a certain depth (60–90 cm). A farmer can manage the drilling machine easily as a typical farming activity.

Drilling machine attached to tractor



(1) Cut soil column and push it up, forming a space
(2) Cut section of side soil and slide it into the space created in step 1
(3) A water conduction cavity complete (Cut-drain)
Mole-drain formation process

Fig. 3 Drilling machine and Cut-drain

The Cut-drain can act as a supplemental drain when used as a connection to the main drain. It can also lead water connecting to a field ditch (**Fig. 4**). A Cut-drain is constructed without any material. The soil texture most appropriate for Cut-drain construction is one with high clay and low sand content. In case of loam, Cut-drain durability is short.

As a Cut-drain is formed only by soil, there is a possibility of collapse caused by excessive preferential flow. According to soil profile surveys in the trial Cut-drain fields, some cavities of Cut-drains collapsed after irrigation or leaching operation because of a large amount of preferential flow. This preferential flow could be mitigated by irrigating the furrows where the blades would be inserted before construction (Okuda et al., 2017). However, it is advisable to construct Cut-drains before every leaching operation to ensure the cross-sectional area of water flow.

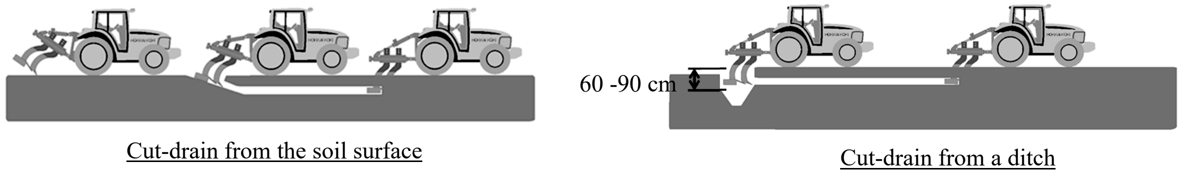


Fig. 4 Examples of execution in construction work

The design of the experimental field is illustrated in **Fig. 5**. According to the soil analyses of the field, the saturated hydraulic conductivity obtained by the falling head permeability test was shown between 7.7×10^{-5} cm s^{-1} and 5.0×10^{-6} cm s^{-1}, and the soil textures were classified as Clay, Clay Loam and Sandy Loam from the International Society of Soil Science standards. Two tile drains, which comprise perforated pipe and rice husk as hydrophobic material, were installed at a depth of around 0.8–1.0 m. The pipe length was 200 m. Cut-drains were constructed at a depth of 0.6–0.8 m. The spacing between Cut-drains was 5 m. Cut-drains cross the main drains to connect the part of rice husk towed by a tractor. In this study field, a 200 m Cut-drain was constructed in a single pass across the field. The Cut-drain direction was the same as the field gradient.

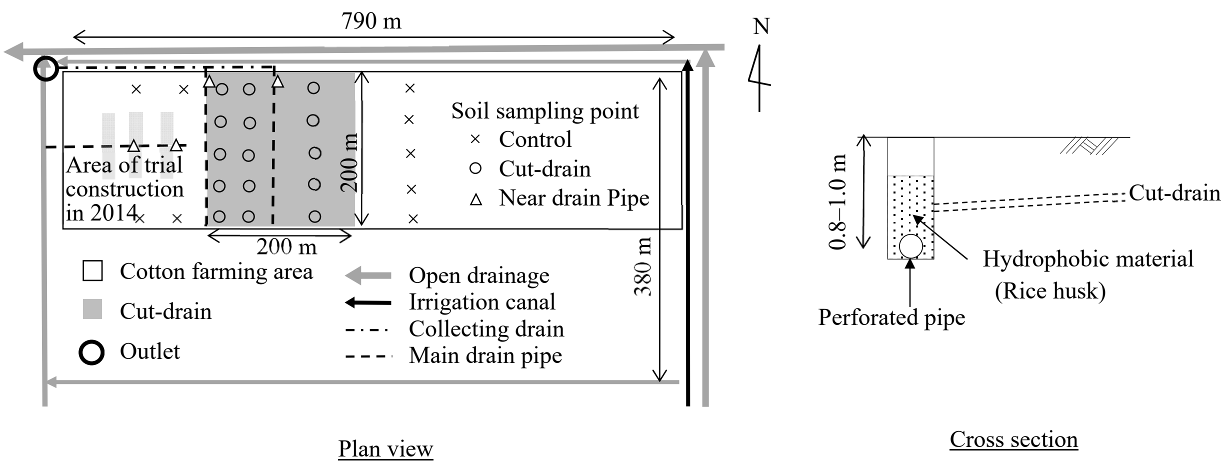


Fig. 5 Layout of experimental field

2.3 Evaluation methods

Shallow subsurface drainage evaluation was carried out in terms of water and soil salinity and crop yield.

2.3.1 Water salinity

The irrigation and discharged waters were taken from the irrigation canal and subsurface drainage outlet, respectively, to measure the electrical conductivity of water (EC_w).

2.3.2 Soil salinity

The soil samples were taken before (December 2016) and after leaching (February 2017) at five distinct layers (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm), using manual auger boring. The number of samples taken from the control field, Cut-drain field, and near tile drain pipe were 45, 75, and 20 (9, 15, and 4 sets), respectively. The sampling points are also shown in **Fig. 5**.

EC of 1:1 suspension was converted to EC_e using an empirical formula developed by the Research Institute of Irrigation and Water Problem (RIIWP), Uzbekistan (Shirokova et al., 2000).

2.3.3 Cotton yield

Cotton yield in terms of weight of cotton was measured to evaluate the effect of the shallow subsurface drainage. The sampling method was to pick cotton in a 1.1 m length by 0.9 m width of ridge and furrow so that the sampling area was equivalent to 1.0 m^2. Four samples were taken near each soil sampling point.

3. Results and Discussion

3.1. Water salinity

After leaching, high EC_w was observed at the subsurface drainage outlet. The EC_w of irrigation water and discharged water were around 1.16±0.02 (n=3) and 10.5±1.3 (n=20) dS m^{-1}, respectively, on average. This indicates that the discharged water contained more salt in the soil. The discharged water was observed after a rain event in April when the groundwater level became less than 1.5 m from the ground surface. Therefore, the surface water (leaching water and precipitation) may have had a predominant role in the discharged water salinity.

3.2 Soil salinity

The average values of soil salinity (EC_e) in the upper surface layer (0–60 cm) and lower layer (60–100 cm) before and after leaching are shown in **Fig. 6**. Percentage reductions of soil salinity after leaching are also shown in **Fig. 6**. After leaching, the relative soil salinity of the upper layer of the control field, Cut-drain field, and near the drain pipe were 67%, 62%, and 50%, respectively. The soil salinity of the upper layer with a shallow subsurface drain was slightly lower than the control. However, there was no significant difference ($p<0.05$) based on the analysis of variance (ANOVA) among the fields with a large dispersion of soil salinity.

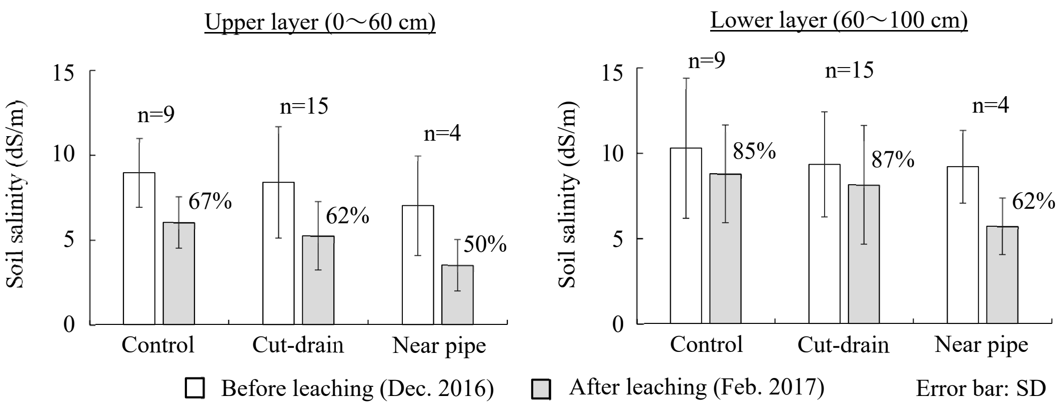


Fig. 6 Rate of soil salinity change

3.3 Cotton yield

The yield survey results are shown in **Fig. 7**. During the cultivation period from May to August 2017, irrigation was conducted between July and August. The total irrigation depth was approximately 400 mm based on a farmer's interview. The precipitation was 9 mm during the cultivation period. The groundwater level kept decreasing from around 1.2 m to 3.0 m in the whole field except during the irrigation period. The cotton yields in the control field, Cut-drain field, and near the pipe drain were 3.3, 3.9, and 4.0 t ha^{-1}, respectively. There is a significant difference in yield based on ANOVA. The Cut-drain field produced approximately 18% higher yield compared with the control (t-test, $p<0.01$). This result indicates that shallow subsurface drainage could be an effective measure in a high salinization field to improve crop yield.

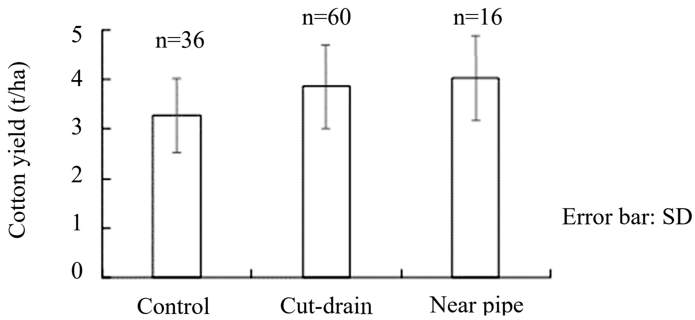


Fig. 7 Cotton yield in 2017

4. Conclusion

Shallow subsurface drainage used in combination with a Cut-drain can help discharge excess water from a field to the open drainage area even during a period of high drainage water level. High EC_w value at outflow was observed during a leaching period and then again in the spring after a rain. Shallow subsurface drainage could remove a significant amount of salt from the field by leaching in addition to that removed by rain. In this study, the influence on soil salinity was not clear. Further studies are therefore necessary to clarify this point. According to the yield survey, an approximately 20% increase in cotton yield was observed in the subsurface drainage field compared with the control field. This technology may be employed as an effective measure to improve agricultural productivity.

One point of discussion is that shallow subsurface drainage technology cannot control deep groundwater. Therefore, further research is needed to clarify the long-term effect or negative effect caused by groundwater levels.

Acknowledgments

We gratefully acknowledge the Farmers' Council of Uzbekistan, Hydro-Geological Melioration Expedition (HGME), RIIWP under the Ministry of Agriculture and Water Resources, and farmers in Syrdarya Region.

This research was also partially funded by the Ministry of Agriculture, Forestry and Fisheries, Japan.

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*The above article was reprinted from "Journal of Arid Land Studies, Vol. 28, No. S, pp. 127-130 (2018)" by courtesy of the Japanese Association for Arid Land Studies.

Salt Pushing Effect to the Side of the Ridge by Fixed Skip Furrow Irrigation
- Case study in the Republic of Uzbekistan -

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Summary

In Central Asia, secondary salinization caused by incorrect irrigation has become a serious problem. Water-saving techniques, drainage improvements, and leaching have been adopted as general measures to mitigate salinization. However, the construction of water-saving and drainage facilities requires plenty of funds. A relatively easy and inexpensive water-saving method is skip furrow irrigation (SFI), by which every alternate furrow is irrigated. In regular SFI, furrows are irrigated alternately (ASFI) during each irrigation event. However, if the irrigation furrows are fixed (FSFI), the salts in the soil might be pushed towards the other side of the ridge. To analyze this salt distribution, a field study comparing every furrow irrigation (EFI), ASFI and FSFI was conducted at a farmland in Uzbekistan. In EFI, the salt content in the center of the ridge increased. Also, in ASFI, the salt content decreased at the wet side of the ridge but after second irrigation, increasing at the center of the ridge. Whereas in FSFI, the salt content on the left (dry) side of the ridge increased, indicating a salt pushing effect. The findings of this study suggest a possibility of more efficient removal of the salt in the surface soil by combining FSFI and the dehydration method.

Keywords
Salinization, Water-saving, Furrow irrigation, Skip furrow irrigation

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1. Introduction

1.1 Background

Soil salinity is one of the major abiotic stresses causing reduced agricultural productivity worldwide. Salinization of arable land has dramatically increased over the last few decades (Martin et al, 2012). The main cause of secondary salinization is the inflow of salt with irrigation water, followed by an increase in the groundwater table due to excessive irrigation and poor drainage. In the absence of leaching, salt accumulates in the soil, especially in the topsoil, because of water loss through evaporation and root uptake (Devkota et al, 2015). Therefore, to mitigate salinization in general, water-saving techniques and drainage improvements should be undertaken as precautionary measures, with leaching being popular among farmers as a salt removal measure because of its inexpensiveness.

1.2 Salinization in Central Asia

In Central Asia, where there are extensive arid and semi-arid areas, secondary salinization caused by inappropriate water management techniques has become a serious problem, with major influences on agricultural production. In Central Asia, large scale irrigation development was conducted during the 1960s (in the Soviet Union era) in the Amu Darya and Syr Darya river basins, which were previously steppe or desert areas. In particular, Republic of Uzbekistan (hereinafter Uzbekistan), cotton production occurred on developed farmland. Although it contributed greatly to the agricultural production of the former Soviet Union, incorrect water management techniques caused severe salinization. As a result, Uzbekistan has the largest salt affected farmlands among all the Central Asian countries (**Table 1**) (Karen, 2013). Salt affected farmland is defined as a farmland where the electrical conductivity of a saturated extract of the soil (EC_e) is higher than 2 dS m^{-1}.

Table 1. Salinized area of the total area under irrigation in Central Asia

Country	Area equipped for irrigation		Area salinized by irrigation		
	Year	ha	Year	ha	(%)
Uzbekistan	2005	4,198,000	1994	2,141,000	51
Kyrgyz	2005	1,021,400	2005	49,503	5
Tajikistan	2009	742,051	2009	23,235	3
Kazakhstan	2010	2,065,900	2010	404,300	20
Turkmenistan	2006	1,990,800	2002	1,353,744	68
Total		10,018,151		3,971,782	40

Source: Irrigation in Central Asia in figures (Karen, 2013, FAO Water Reports 39, pp 68)

In Uzbekistan, although 27 years have passed since the country's independence from the Soviet Union, in 1991, government control of cotton and wheat production is still ongoing. Current cotton and wheat production are carried out by an agricultural corporation called "*Fermer*," which leases government farmland under a long-term agreement (Onishi, 2012). Cultivation on such *Fermer* farms usually involves furrow irrigation with low application efficiency. Under the current scenario, it is difficult for *Fermer* to install water-saving and drainage facilities because of their high costs. As a result, leaching is the only practical measure available to them because of low cost. However, there is concern about the influence of the hardpan layer, which is formed by the long-term treading pressure of agricultural machines, on the effectiveness of leaching.

A relatively easy and inexpensive water-saving method is skip furrow irrigation (SFI), which is often called alternate furrow irrigation. In this method, instead of irrigating all furrows, water is supplied to one of the two neighboring furrows (i.e., alternate furrows), viz., to one furrow for every two ridges (**Fig. 1**). In conventional SFI, the wet furrows are alternated during each irrigation event (ASFI) (Brouwer et al., 1985).

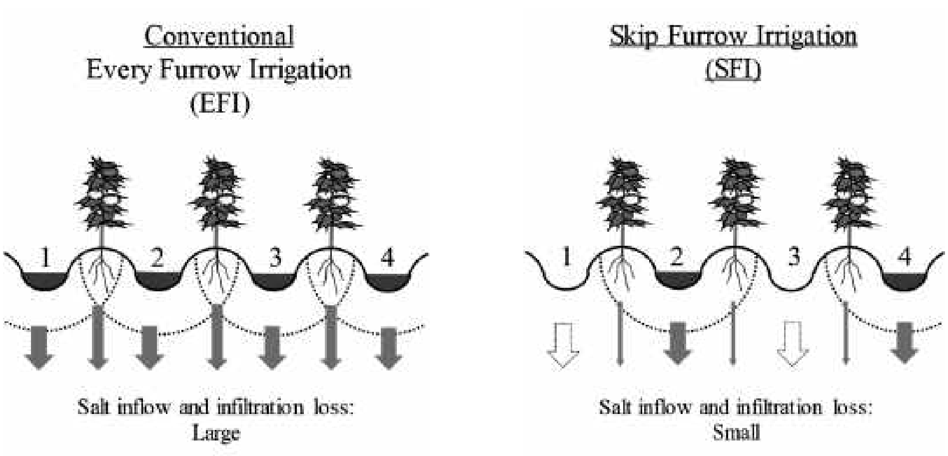

Fig. 1 Concept of skip furrow irrigation

The advantage of SFI is that it can reduce the amount of water supplied, and reduce infiltration and evaporation loss, as well as lateral flow, in the non-irrigated furrows. Alan and Karen (1994) reported that approximately 58% of irrigation water was saved without significant reduction in peppermint yield when SFI was applied, compared with when every furrow irrigation (EFI) was used. However, the disadvantages of SFI are that it takes a longer time to completely irrigate the whole field and a larger labor force to relocate the irrigation furrow during each irrigation event (Alan and Karen, 1994). Typically, crops are planted in the center of the ridges, however, in EFI, the salt in the soil tends to accumulate in the highest point of the ridge (Brouwer et al., 1985). To avoid this, if the irrigation furrows are fixed in SFI (FSFI), then the salts in the soil might be moved towards to dry side of ridge, rather than being accumulated in the center of the ridge. According to Devkota et al. (2015), more salt was accumulated at the dry side of ridge under FSFI. These authors also reported that the irrigation-induced movement of salts in the shallow soil layer, up to 15 cm depth, was larger than that in the deeper layers.

In the present study, to develop an efficient furrow irrigation technique that can reduce water usage and mitigate salinization, we researched the fixed skip furrow irrigation (FSFI) in which the wet furrow is fixed, unlike in ASFI where it is not fixed, and evaluated its effectiveness by comparing it with EFI and ASFI in a cotton field in Uzbekistan.

2. Materials and methods

2.1 Study area and site description

In the Syrdarya Region 98% of the irrigated farmlands is salt affected (Onishi et al, 2017). This area was selected as the study area in the present study (**Fig. 2**). Daily average temperature in the Syrdarya Region increases to 30 °C in summer and decreases to approximately 0 °C in winter. The annual precipitation is approximately 320 mm, however, the cumulative precipitation from June to September is very low (approximately 20 mm).

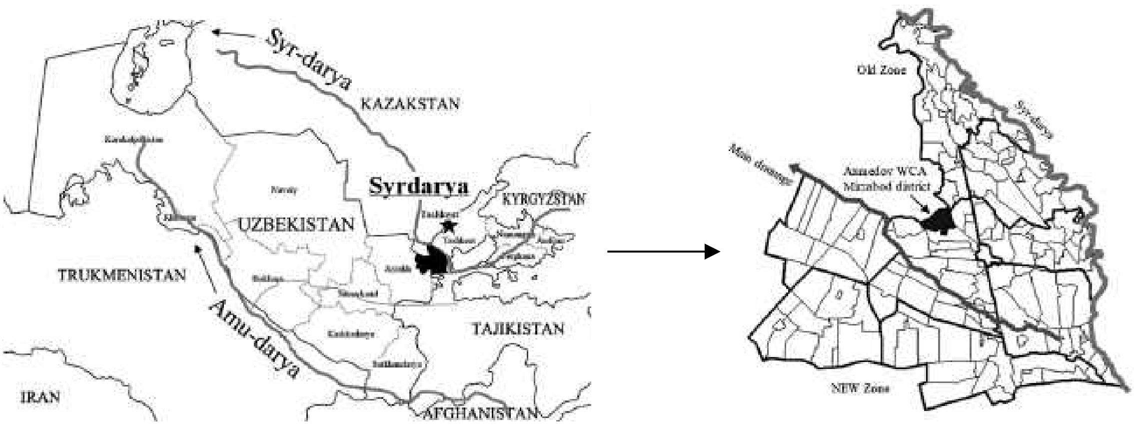

Fig. 2 Location of Syrdarya Region and Axmedov Water Consumer's Association (WCA)

The field study was conducted at the Nozima Durdona Fayz farm (hereinafter N farm), which belongs to the Axmedov Water Consumer's Association, and is located in the Mirzaabad district. According to the Hydro-Geological Melioration Expedition (HGME) of Uzbekistan, 99% of the irrigated farmland is salt affected in the Mirzaabad district. The N farm is approximately 50 ha in area, with a length of approximately 820 m from the East to the West, and 620 m from the North to the South. The irrigation channel is located along the eastern end of the farm, and drainage channels have been dug in the northern and western sides of the farm. The bulk density of the surface soil layer is 1.4 g cm^{-3}, whereas in depths of 20 cm to 40 cm the bulk density is higher, at 1.6 g cm^{-3}, indicating that the N farm had a hardpan layer that might have been compacted by the pressure of agricultural machinery operated for long.

2.2 Experimental set up and treatment

The experiment was conducted during the cotton cultivation period on the northeastern side of the N farm from 11th of July to 6th of September in 2017. Three treatments (EFI, ASFI, and FSFI, **Fig. 3**) with three repetitions, i.e., nine plots in total, were set up.

South side North side

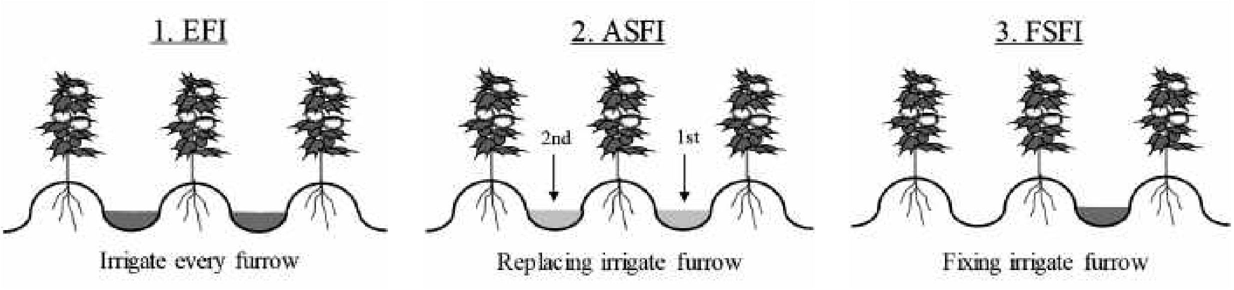

Fig. 3 Treatment of field experiment

In the experiment, the ridge and furrow size were 50 cm and 40 cm, respectively, based on the size widely used throughout Uzbekistan. Plot width and length were 1.3 (one ridge and two furrows) and 4.0 m, respectively. The direction of the furrows was from the East to the West. (**Fig. 4**)

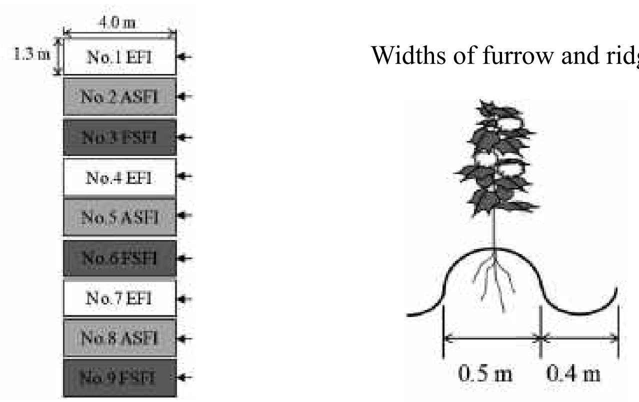

Fig. 4 Plot design of field experiment and ridge and furrow size

In EFI 0.52 m^3 (5.2 m^2 × 0.1 m) of water was applied with reference to 100 mm, on the basis of the standard amount applied in Uzbekistan, and half of this value (i.e., 0.26 m^3) was applied in the ASFI and FSFI treatments. Water was supplied using a gasoline pump (LGP 20-A, Leo Group Co, Ltd, Binhai town, Wenling city, China, discharge rate 5 Ls^{-1}). During the first irrigation in ASFI, the northern side furrow was watered, and then South side furrow was watered during the second irrigation (**Fig. 3**). In FSFI, the wet furrow was fixed at northern side. The first and second irrigations were conducted on July 12 and 25, 2017, respectively, and the electrical conductivity of the irrigation water during these events was 1.08 and 1.06 dS m^{-1}, respectively.

2.3 Soil salinity measurement

Soil salt distribution before and after irrigation in each treatment was measured by soil sampling. The soil was sampled from 0, 1, 5 and 10 cm depths at the center, left, and right side of the ridge in a center of each plot (**Fig. 5**).

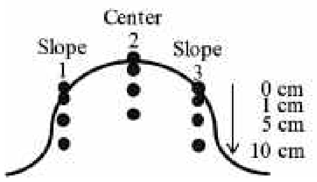

Fig. 5 Soil Sampling point of field experiment

The electrical conductivity of the 1:1 suspension of the soil samples ($EC_{1:1}$) was measured. The salt concentrations of the suspensions were estimated using the $EC_{1:1}$. Assuming that the major ions were calcium and chloride, total dissolved solids were calculated using the following formula obtained from a laboratory calibration:

$$c_{1:1} = 0.50\sigma^{1.10} \quad (1)$$

where, c is the concentration of the suspension (mg g^{-1}) and σ is the electrical conductivity of the suspension (dS m^{-1}).

The weight of salts per volume, θc (mg cm^{-3}) was calculated using the following formula (2).

$$\theta c = c_{1:1}\, Madd/V \quad (2)$$

where, θc is the $CaCl_2$ weight per unit volume (mg cm^{-3}), c is the $CaCl_2$ concentration of suspension, M_{add} is the weight of added distilled water (g), and V is the soil volume (cm^3).

3. Results and Discussion

3.1 Salt distribution

Soil sampling was conducted 1 day before and 2 days after each irrigation (July 11, 14, 24, and 27, 2017). July is a dry season. A rainfall of 0.4 mm was observed on July 13. The distribution of salt content before and after irrigation under each treatment is shown in **Fig. 6**. Contour map was drawn under assumption of linear distribution between two points.

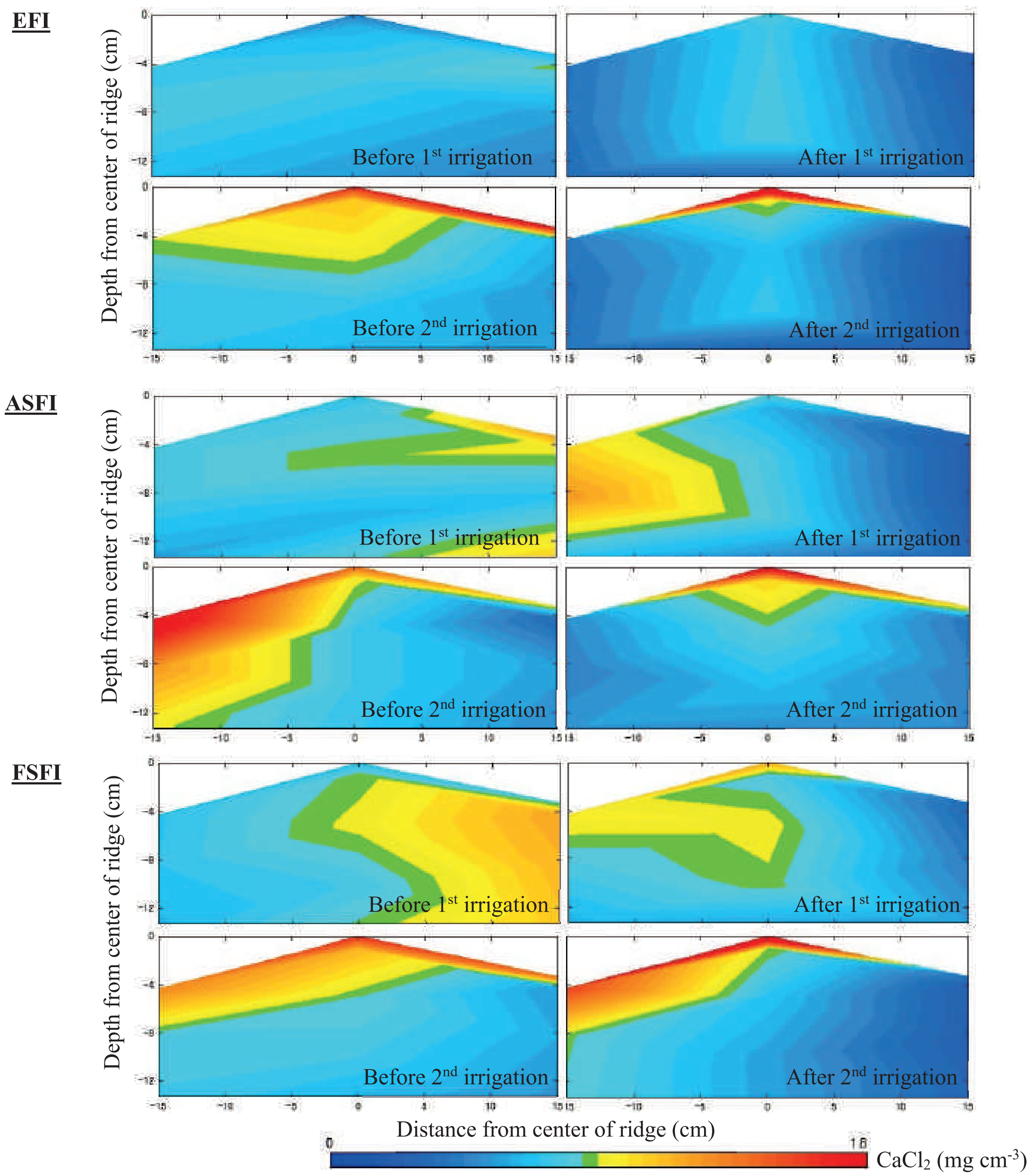

Fig. 6 Salt distribution before and after irrigation

Salt was found to be accumulated at the soil surface in all the treatments; however, the pattern of accumulation was different. In EFI, the salt content on the left and right side of the ridge decreased but increased at the center of the ridge. In ASFI, the salt content decreased at the wetting side of the ridge (first irrigation right side, second irrigation left side), whereas after the second irrigation, the salt content increased at the center of the ridge. In contrast, in FSFI, the salt content in the right (wetting) side decreased, whereas it increased on the left (dry) side of ridge. This indicates the salt pushing effect of the FSFI.

These results indicate that the salts in the soil might have moved with flow of irrigation water in the soil. Therefore, in EFI, salts were accumulated in the center of the ridge where irrigation water from both sides merged. In ASFI, salts were transported to the dry side of the ridge; however, the place of the flow changed at each irrigation, resulting in salt accumulation in the center of the ridge. In FSFI, since the place of water flow during irrigation was kept constant, salts were accumulated on the side of the ridge. In addition, the effect of irrigation on the change of salt accumulation was higher in the surface soil (0 cm depth) than in the deeper soil.

3.2 Cotton yield

Cotton yield survey was conducted on September 11, 2017. The fresh cotton weights of each plot (3.6 m^2) were measured (**Fig. 7**).

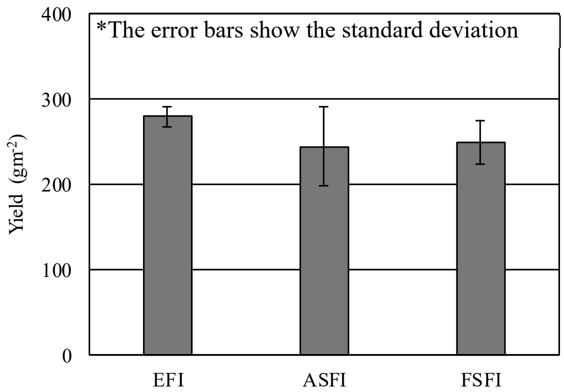

Fig. 7 Cotton yield in each treatment

Cotton yield was lower in the ASFI and FSFI treatments by 13 and 11%, respectively, than that in the EFI treatment, although there was no significant difference and the standard deviation of EFI was smallest. However, since the amount of water applied was halved in the ASFI and FSFI treatments only during the test period, both ASFI and FSFI had the same amount of water applied as EFI during the other periods; this might be why the decrease in cotton yield was not as large. *Fermer* may accept such slight reduction in yield if they can increase cultivated area with saved water or volumetric water pricing is introduced.

4. Conclusion

In the present study, we evaluated the distribution of salt in the soils under EFI, ASFI and FSFI, focusing on surface soil (down to 10 cm depth) in which water consumption and salt changes were high before and after irrigation. We found that the salts in the soil were transported with water flow onto the ridge of the furrows, and if the irrigated furrows remained constant during each irrigation, it was possible to push the salts in the soil to the side of the ridge. Large amounts of salt pushed by FSFI were accumulated along the ridge side, especially in the surface layer (0 cm depth), which was greatly affected by evaporation demand. Therefore, FSFI could be an effective measure for mitigating salinization.

However, even if the salt in the soil is successfully accumulated on the surface layer with FSFI, there is the possibility of it returning to the deeper layers again if it is not removed. An effective method of removing salt from the surface soil is the dehydration method. In the dehydration method, the powerful evaporation demand in arid areas is utilized to collect salt from the soil onto a cloth or a sheet that has been laid on the surface (Abe et al, 2000). There is a possibility that salt in the surface soil can be removed more efficiently by combining the FSFI and dehydration methods.

Further research is required to evaluate the desalination effect of the combined FSFI and dehydration methods, and verification of the efficacy of this technique on cotton yield. If proven effective, this combined technique might be useful as a salt removal method to compensate for leaching during winter in the arid areas. In addition, to evaluate water-saving effect of FSFI, it is necessary to monitor supplied water for cotton in whole cultivation period.

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*The above article was reprinted from “Journal of Arid Land Studies, Vol. 28, No. S, pp. 155-158 (2018)” by courtesy of the Japanese Association for Arid Land Studies.

Acknowledgments to journals

The editors gratefully acknowledge the generosity of the Japanese Society of Irrigation, Drainage and Rural Engineering, the International Society of Paddy and Water Environment Engineering, the Japanese Association for Arid Land Studies, and the Japanese Society of Sand Dune Research, for granting permission to reprint and translate their previously published materials for this Working Report. The journal titles and publishers/names of societies are listed below.

Title of article	Journal title and Name of society
Current status and problems of the drainage system in Uzbekistan	Journal of Arid Land Studies, Vol. 25, No. 3, pp. 81-84 (2015), The Japanese Association for Arid Land Studies.
Composition and classification of salts in surface water and groundwater in a semi-arid irrigated area - Case study in Mirzaabad district, Uzbekistan -	Sand Dune Research, Vol. 64, No. 3, pp. 101-111 (2018), The Japanese Society of Sand Dune Research
Actual Condition of Vertical Drainage for Farmland Salinization in the Republic of Uzbekistan	Water, Land and Environmental Engineering, Vol. 83, No. 5, pp. 381-384 (2015), The Japanese Society of Irrigation, Drainage and Rural Engineering
Water-saving Effect of Simplified Surge Flow Irrigation on Irrigated Farmlands in Arid Areas - A Case Study in the Republic of Uzbekistan -	Journal of Arid Land Studies, Vol. 27, No. 3, pp. 91-101 (2017), The Japanese Association for Arid Land Studies
Suitable inflow rate and furrow length for simplified surge flow irrigation	Paddy and Water Environment, Vol. 17, Issue 2, pp. 185-193 (2019), The International Society of Paddy and Water Environment Engineering
A Trial of Desalinization by Using a Mole-Drain in the Republic of Uzbekistan	Water, Land and Environmental Engineering, Vol. 83, No. 7, pp. 541-544 (2015), The Japanese Society of Irrigation, Drainage and Rural Engineering
Problems and Measures for the Adoption of Cut-drain and Its Applicability to Soil Conditions in Uzbekistan	Irrigation, Drainage and Rural Engineering Journal, Vol. 85, No. 2, pp. II_83-II 90 (2017), The Japanese Society of Irrigation, Drainage and Rural Engineering
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Acknowledgment to reviewers

The editors gratefully acknowledge the reviewers, whose names and affiliations are listed below, for their assistance and significant contributions to the publication of this Working Report.

Chikara OGURA	Institute for Rural Engineering, NARO
Masahiro HYODO	Faculty of Agriculture, Tottori University
Shinpei NAKAGAWA	Akita Agricultural Experiment Station
Tetsuji OYA	JIRCAS

JIRCAS Working Report No.88 ISSN 1341-710X

Development of subsurface drainage and water-saving irrigation technology for mitigation of soil salinization in Uzbekistan

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Published by
Japan International Research Center for Agricultural Sciences

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Tel. +81-29-838-6313
https://www.jircas.go.jp/

JIRCAS Working Report No.88
令和２年３月５日発行

発行者：国立研究開発法人　国際農林水産業研究センター
理事長　岩永　勝
〒305-8686　茨城県つくば市大わし 1-1
TEL　029(838)6313（代表）

印刷：　朝日印刷株式会社　つくば支社