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Effects of soil texture and groundwater level on leaching of salt from saline fields in Kesem irrigation scheme, Ethiopia

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Abstract: In Ethiopia, soil salinity has become a challenge for agricultural production in irrigated arid and semi-arid areas. This research investigates the effectiveness of leaching salt remediation under different soil textures and groundwater tables. Leaching was conducted in the bare parts of three abandoned saline fields. Soil texture of Field 1 (F1) is sandy loam while Field 2 (F2) and Field 3 (F3) are clay loam. The F1, F2, and F3 groundwater was located at 1.8, 1.5 and > 3 m, respectively. The leaching requirement water levels were 15, 20, 25, and 30% higher than the evaporation of the bare field needed for four consecutive weeks, respectively. The results of this study show that, after four days of leaching, the salinity of F1 with sandy loam texture was significantly ($P < 0.05$) and more strongly reduced than for the other fields exhibiting clay loam texture. For F1, salinity was reduced from 16.3 to 6.2 dS/m and from 12.4 to 5.5 dS/m at depths of 0–30 and 30–60 cm, respectively. In head parts of F1 and F3, the salinity level was reduced to 2.0 dS/m. However, in F2 with shallow groundwater and clay loam texture, the salinity levels were slightly higher after leaching, i.e. from 11.2 to 12.0 dS/m and from 8.1 to 11.6 dS/m at 0–30 and 30–60 cm depths, respectively. In our experiment, effective leaching was achieved only in the field with sandy soil and deeper groundwater table. We saw that the application of leaching with surface drainage at shallow groundwater levels may further exacerbate salinity problems. For such situations, the use of subsurface drainage could sustain the groundwater depth and prevent additional salinization. On clay-textured fields with shallow groundwater table, a prolonged leaching application is necessary to reduce the salt contents.

Keywords: arid; furrow irrigation; leaching; soil salinity; water

The Awash River Basin is the most utilized basin in Ethiopia for irrigated agriculture and hydropower generation (Awulachew *et al.* 2007). The Awash River flows entirely in Ethiopia, from the highlands (4195 m) to the arid and semi-arid flat lowland of Afar (210 m). Hence, the structure of the Afar lowland topography is favouring easy diversion of the Awash River for use in irrigation. As a result, in recent years irrigated agriculture has expanded more strongly in these arid and semi-arid areas than ever before.

However, soil salinity problems have severely compromised the crop productivity of the established dryland areas' irrigation schemes. Lack of a functional drainage system (Taddese 2001), uncontrolled irrigation practice and poor irrigation management (Ayenew 2007), shallow and highly saline groundwater

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fluctuation and improper irrigation canal installations (Gelaye *et al.* 2019) were the main causes of soil salinity problems. It becomes obvious that in the long run soil salinity will become a major environmental, economic and social challenge for irrigated agriculture of Ethiopian arid areas. Proper irrigation management and timely salinity reclamation are needed to sustain the productivity of irrigated agriculture in these areas. Otherwise, over time, the salt added to the soil by irrigation water will accumulate in the soil, which will cause a significant crop yield loss. When salinity develops in the crop root zone and exceeds crop salinity tolerance thresholds, yield declines or total crop failure can lead to food insecurity and a severe financial loss on irrigation agriculture investments.

In areas with high evapotranspiration, the accumulation of salinity is very high as large amounts of irrigation water are added to the soil every season. For such situations, scheduled application of leaching or leaching requirement (LR) based on the soil salt content is a way to mitigate soil salinity. The leaching-induced soil desalinization method is an effective established method recommended by several authors (Rhoades 1974; U.S. Salinity Laboratory Staff 1954; van Hoorn *et al.* 1969). Among existing salinity mitigation methods, leaching is by far the most effective procedure for removing salts from the root zone of soils (Abrol *et al.* 1988; Oster 1994). Indeed, leaching may be very effective to reduce severe soil salinity within a short time. However, for effective leaching remediation, area-based leaching investigations and precise recommendations are required based on soil texture, depth of groundwater table, and soil salinity levels. Field-based studies addressing these issues are crucial for future soil salinity mitigations and provide important inputs for policymakers of irrigation in arid areas to identify irrigated land management options.

The goal of this study was to investigate the final spatial distribution of soil salinity of formerly irrigated, abandoned bare fields with different soil texture and depth of groundwater table, and to determine the effectiveness of leaching using furrow irrigation for the reduction of soil salinity.

MATERIAL AND METHODS

Description of the study area. The study was conducted in the Kesem River catchment in the middle part of the Awash River basin (Figure 1) which is in the eastern part of Ethiopia. The Kesem irrigation scheme is one of the newly established (in 2009) irrigation schemes in the middle Awash Basin to irrigate 20 000 ha of sugarcane plantations using a furrow irrigation method. However, after ten years of sugarcane production under irrigation, over 200 ha of the land cannot be cultivated due to high soil salinity accumulation. Before sugarcane plantations in 2009, most parts of the Kesem scheme did not have any irrigation or rained cultivation history. The study area is located between 9°7' to 9°26' N and 40°9' to 40°30'E at elevations ranging from 760 to 850 m. Soil textures vary from clay loam to sandy loam. Mean soil bulk density is 1.3 g/cm^3 and the root zone soil salinity varies from 2 to ≥20 dS/m. Annual temperature varies from 18 to 41°C. Mean annual rainfall is about 590 mm and annual evapotranspiration in the area has been estimated at approximately 1800 mm. The Kesem River dam water is conveyed to the fields by an open primary canal to tertiary canals, and then hydro-flumes discharge the water to the field furrows. In terms of water salinity, the Kesem irrigation water is high-quality water which originates from the highland areas. The lower stream canal average salinity level of the irrigation water was 0.32 dS/m and the pH was 7.6.

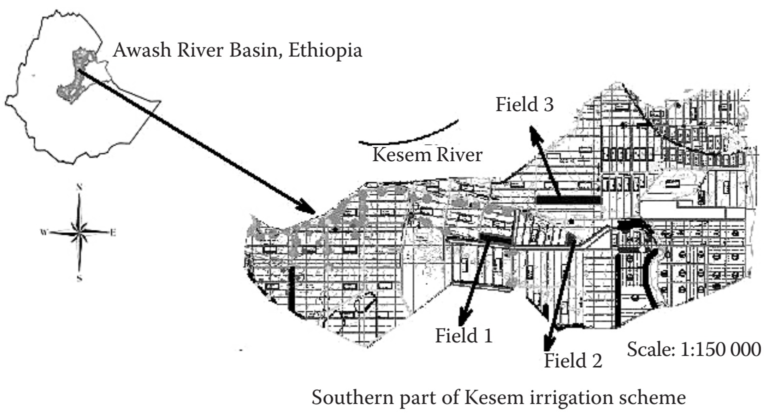

Figure 1. Map of the study area in the Kesem irrigation scheme where the three experimental fields are found

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Table 1. Experimental plot soil properties and particle size distribution

Soil properties		F1	F2	F3
Texture type		sandy loam	clay loam	clay loam
	sand	64	25	27
Particle size distribution (%)	silt	17.5	43	42
	clay	18.5	32	31
pH		7.3	8.1	7.3
Salinity (dS/m)		16.4	12.0	18.9
Saturated hydraulic conductivity (mm/h)		10.3	6.9	8.7

Experiment setup and field selection. The study area covers different soil textures with varying groundwater. Field-based experiments were launched in three separate highly saline sugarcane fields, i.e. Field 1 (F1), Field 2 (F2), and Field 3 (F3). These saline fields are found in different parts of the irrigation scheme (Figure 1). Due to high salinity in these three fields, no sugarcane grown was on some parts of the fields. Leaching experiments were carried out on these bare areas of the fields.

The soil texture of F1 is sandy loam while F2 and F3 are clay loam. After three continuous irrigation seasons, the groundwater table rose from 2.8 to 1.8 m for F1 and from 1.7 to 1.5 m for F2. F3 had a deep groundwater table of 2.8 m and no change was detected. For the field measurements, plots of 42 × 42 m, 22 × 32 m and 22 × 22 m were selected for F1, F2, and F3, respectively.

Particle size distribution was determined using a combined wet sieving and sedimentation method (Bernhardt 1994). Saturated hydraulic conductivity was measured in each plot at 30-cm depth using a 2800 Guelph Permeameter (Soilmoisture Equipment Corporation, USA). Both soil pH and electrical conductivity (EC) were measured using HI 991300 meter (Hanna Instruments, USA). The main soil properties of these plots are presented in Table 1.

A one-meter-deep trapezoidal surface drainage ditch was excavated and used as a temporary drainage outlet (Figure 2). This procedure was adopted because the excavated soil was used to build a ridge at the end of the field to prevent uncontrolled water outflow and to enhance prolonged ponding. An impermeable plastic was placed on the ditch canal surface to prevent percolation at the ditch and for precise measurement of the drainage water depth.

To cover the entire high ridge (40 cm deep) furrow field with water, accelerate the leaching process and flush the surface accumulated salt efficiently, the high ridge furrows of the fields were demolished (Figure 5). The depth of incoming water to the experimental fields and of outgoing drainage water was measured using Parshall flumes. To detect the groundwater level during the experiment, piezometers were installed at the centre of the experimental fields.

Salinity measurement and leaching requirement estimations. In addition to the soil salinity levels, the leaching requirement (LR) estimation depends on the irrigation methods. For furrow irrigation, Savva and Frenken (2002) recommended about 10–30% more irrigation water than needed by the crops to be applied for leaching purposes.

For LR and total applied water determination, seasonal evaporation (E) of the experimental site was considered. The leaching experiment was done on bare land, and, hence, the crop coefficient was not included for LR estimation. The leaching experiments were conducted from June to August. The seasonal evaporation was estimated by the pan evaporation

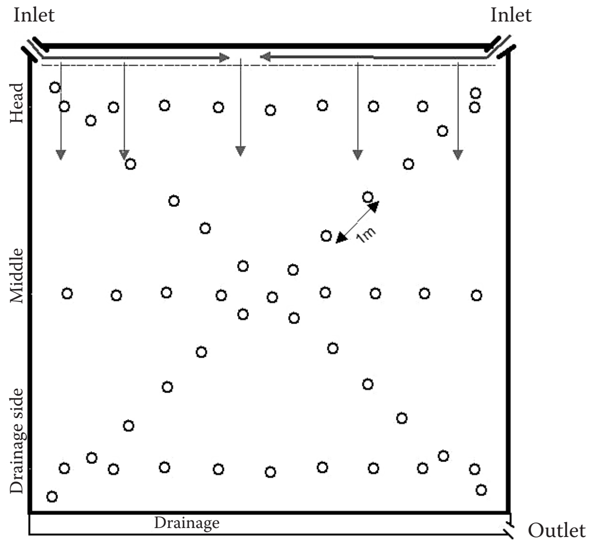

Figure 2. The layout of the experimental plots; the water distribution in the plot is represented by arrows, and the circles represent the location of soil sampling points

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Table 2. Estimated applied water (the same values used for each experimental plot)

Period	Soil evapotranspiration (mm/season)	Leaching requirement	Total applied water (mm/week)
Period 1 (1–7 days)	1800	0.13	40
Period 2 (7–14 days)	1800	0.17	57 = 42 + 15 (flushing)
Period 3 (14–21 days)	1800	0.20	43
Period 4 (21–28 days)	1800	0.23	45

method (Penman 1948) to about 1800 mm/season and there was no rainfall event recorded a week before and during the experiments. The total applied water (AW, mm/season) was estimated according to Ayers & Westcot (1985):

$$AW = ET/(1 - LR) \quad (1)$$

However, the bare soil AW was estimated based on the seasonal evaporation as

$$AW = E/(1 - LR) \quad (2)$$

The practiced irrigation schedule at the experimental site is once a week. In this experiment, applied water of each irrigation day was estimated from seven days (Eq. (2)) of the estimated total applied seasonal irrigation water.

As soil properties do not directly affect the LR (Corwin *et al.* 2007), we used the same LR value for the three fields. LRs of 15, 20, 25, and 30% of the evaporation were considered, resulting in LR values of 0.13, 0.17, 0.2, and 0.23, or 40, 42, 43, and 45 mm surplus water during four consecutive weeks (Table 2). After the total applied water was estimated, four days of leaching application were conducted for four consecutive weeks, i.e. one day per week. Additionally, on the second day of leaching, extra 15 mm water was supplied for flushing.

Disturbed soil samples were collected using an auger before and immediately after the experiment at depths of 0–30 cm and 30–60 cm. The field layout of soil sampling is shown in Figure 2. From five transects soil samples were taken along each line at 1 m distance. The quantity of drainage water and its salinity content (EC_{dw}) were measured using a portable EC measuring device at a 1 : 5 soil/water ratio. The portable EC device was capable of measuring a maximum range from 0 to 3.999 dS/m; however, the salt was diluted using a 1 : 5 soil/water ratio, hence, the salinity reading was multiplied by five and the maximum measuring range of the device was extended to 20 dS/m.

Data analysis. One-way analysis of variance (ANOVA) was performed and comparisons of means were conducted using Tukey's post-hoc test ($P < 0.05$) with SPSS Statistic (Ver. 20.0, 2011).

RESULTS

Salinity reduction and distribution after leaching. After four days of leaching, a substantial amount of salt was removed from the root zones of F1 and F3 (Table 3). However, F2 with a shallow groundwater table showed a small effect in the topsoil and salinity even increased in the subsoil after days of water ponding. While the groundwater table was the main determinant factor for effective leaching, soil texture also affected leaching efficiency. For the sandy soil (F1), average salinity decreased from 16.3 to 6.2 dS/m at a depth of 0–30 cm and from 12.4 to 5.5 dS/m at a depth of 30–60 cm. A lower salt reduction was observed for the clay loam of F3 where salinity decreased from 19.0 to 12.3 dS/m and from 13.3 to 8.7 dS/m at depths of 0–30 and 30–60 cm, respectively (Figure 3). The salinity extent is shown in Figure 3. In some parts of F1 and F3, the salt levels were strongly reduced (down to 2 dS/m) by the employed leaching treatment. Generally, more salt was removed from the sandy soil, and from the top part of the soil rather than from the lower depth.

The initial salt concentration in the soil was extremely high in all plots. It ranged between 5.2 and 20 dS/m in F1, between 1.3 and 20 dS/m in F2 and

Table 3. Effectiveness of leaching for the three different fields

Plots	Salinity (dS/m)	
	before leaching	after leaching
F1	14.4^a	5.8^a
F2	9.9^b	11.8^b
F3	16.2^c	10.1^b

Means followed by the same letter represent non-significant differences at the $P < 0.05$ level

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Table 4. Mean soil salinity distribution after leaching (mean ± SD) at three parts of each plot with 0–30 and 30–60 cm depth

Part of the field	Salinity (dS/m)					
	F1		F2		F3	
	0–30 cm	30–60 cm	0–30 cm	30–60 cm	0–30 cm	30–60 cm
Head	5.5 ± 2.2[a]	5.2 ± 2.7[a]	14.0 ± 6.5[a]	14.1 ± 5.9[a]	14.3 ± 5.7[a]	11.9 ± 7.9[a]
Middle	5.3 ± 2.2[a]	6.6 ± 3.8[a]	11.8 ± 5.1[a]	11.2 ± 3.9[a]	13.1 ± 4.1[a]	7.8 ± 3.8[a]
Drainage	7.7 ± 2.7[b]	4.8 ± 1.8[a]	8.3 ± 5.3[b]	7.1 ± 3.7[a]	9.1 ± 4.9[a]	6.0 ± 3.0[a]

Means followed by the same letter represent non-significant differences between the parts of one field ($P < 0.05$ level)

between 13.5 and 20 dS/m in F3. After the leaching application, a significantly lower amount of salt was detected at a 0–30 cm depth at the drainage side of F2 (Table 4). On the other hand, high salinity accumulation was detected in the head part of F2 (0–30 cm depth) after leaching. However, there was no significant salt accumulation at both depths for F3 and at 30–60 cm for F1 and F2.

In the Kesem irrigation scheme, due to high salinity accumulation in the middle part of the field, the sugarcane plants often show stunted growth and late drying. Indeed, there is no functional drainage for irrigation farming in the Kesem scheme, but there are other ways of salinity level reduction/distribution in the fields. Surface irrigation water may run off over the ridge at the drainage side, which happens during over-irrigation events. This reduces the salt load on the drainage side of the cropped lands. On the other hand, salt from the head side of the fields is washed by the incoming irrigation water, which is lower in salt content compared to the middle part of the fields.

The implications of high ridge furrows on salinity decrease and uniform water distribution. For F1, after the high ridge moulding furrow (40 cm) was demolished combined with surface water flushing at the beginning of leaching day two, a high amount of salt was removed from the soil profile and carried away with the drainage water (Figure 4). Hence, the depth of applied non-saline water (0.32 dS/m) increased from 39 mm on the first leaching day to 57 mm on the second leaching day (Figure 4). On the second leaching day, 15 mm extra water was supplied to compensate for the surface flushing water. This provided an opportunity to dissolve and transport more salts from the top layer of the field to the ditch through flushing. As a result, for F1 and F3 salinity was decreased rapidly. The water distribution with and without the high ridge furrow is shown in Figure 5. The demolition of the ridge helped to submerge the surface of the field with water and to promote the uniform distribution of water to the entire plot and deep percolation. After demolishing the furrow, the EC of the drainage water was ≥20 dS/m on the second leaching day (Figure 4). This salt load flushed out before it could infiltrate into the soil profile. The remaining leaching water (4.2 cm) stayed ponded to percolate down and some amount drained through the ditch. With this flushing and draining, the F1 salinity level of the soil declined from 15 to 9.2 dS/m at 0–30 cm and from 13.2 to 11.0 dS/m at 30–60 cm depth. After this, the soil salt levels further declined

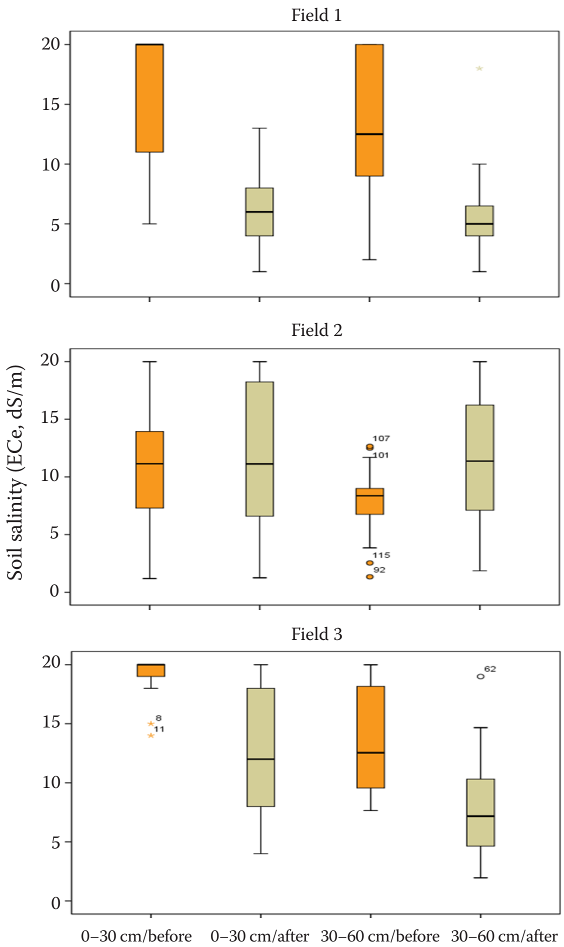

Figure 3. Soil salinity distribution before and after leaching remediation at 0–30 cm and 30–60 cm depths

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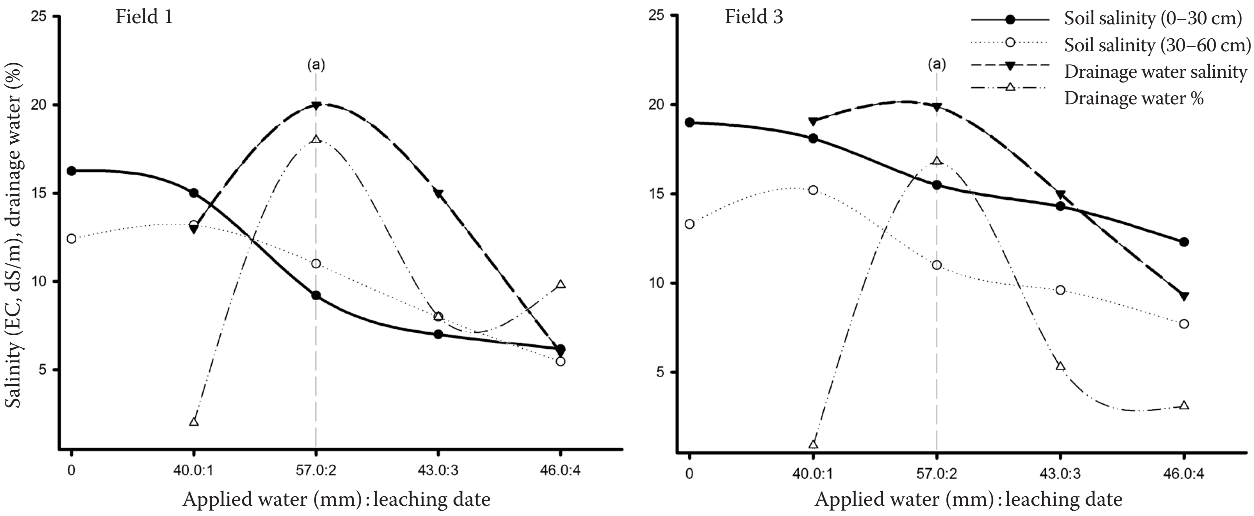

Figure 4. Effect of flushing and sequential application of surplus water on drainage water carrying salt (ECdw, dS/m) and temporal decrease of soil salinity; line (a) at leaching day two represents the time of furrow demolishing and extra flushing

through the fourth day of leaching. Indeed, as a high amount of drainage water flowed out from the plot, the drainage water salinity concentration declined fast over the leaching days (Figure 4).

DISCUSSION

By the tested leaching method, unproductive abandoned saline land could be reclaimed back into productive land. Effective leaching was observed in fields with deeper groundwater table, especially when the soil texture was sandy. After leaching, soil salinity levels were reduced to as low as 2 dS/m in some parts of F1 and F3. Such significantly reclaimed parts of fields have turned into promising productive land to grow even moderately salinity-sensitive crops like sugarcane, maize, lucerne and others. In a furrow irrigation field experiment, Devkota *et al.* (2015) found a comparable result, when salts were reduced to less than 3 dS/m after three to four leaching events. According to Ayers and Westcot (1985), this level of soil salinity (2 dS/m) could increase the yield potential of sugarcane by 90 percent without consideration of other crop production constraints. According to the above authors, the overall yield potential for sugarcane production in the reclaimed fields of our study was improved from 0 to 75 percent for F1 and to 50 percent for F2 considering the post-leaching overall salinity level.

The experimental fields of this study experienced extremely high salinity. To reclaim these fields in a deeper groundwater situation, a large amount of leaching water and continuous leaching application are needed to promote salt leaching from soil (Heidarpour *et al.* 2009). In F1, the salt content of drainage water was rapidly increased along with the increase in a drainage water amount until a certain period. This is because a sequential application of leaching water is important to allowing time for the soil to drain after each application (Ali 2011). However, on the last leaching day of our experiment,

Figure 5. Leaching water distribution before (A) and after (B) furrow ridge demolition

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the drainage water salinity was reduced again as the applied water and drainage water increased.

Although the groundwater table depth threshold may vary depending on soil hydraulic properties and climatic conditions (Rengasamy 2006), our result shows that the employed procedure involving sequential days of ponding worked only for fields with more than 1.8 m groundwater table. If the groundwater table is too close to the surface (in our case F2), the leaching technique may bring adverse effects of increasing salinity. This happens through the upward movement of shallow saline groundwater and its subsequent evaporation on the surface (Ayars *et al.* 2011). In other recent studies, salt accumulation due to groundwater table rise was high in the absence of an efficient irrigation drainage system (Nabiollahi *et al.* 2017). It is therefore important that subsurface drainage systems are installed to control groundwater uprising before irrigation application and leaching treatments (Savva & Frenken 2002). As shown in Figure 6, there is an indication of groundwater rising in F2 of our experiment, because after leaching treatment, the salinity level of the subsoil (30–60 cm) was approaching that of the topsoil (0–30 cm). Usually, with no rise of groundwater, higher salinity levels were found in the topsoil. In the lower and middle Awash Basin, over-irrigation has indeed caused shallow groundwater fluctuations, which have contaminated productive irrigated lands.

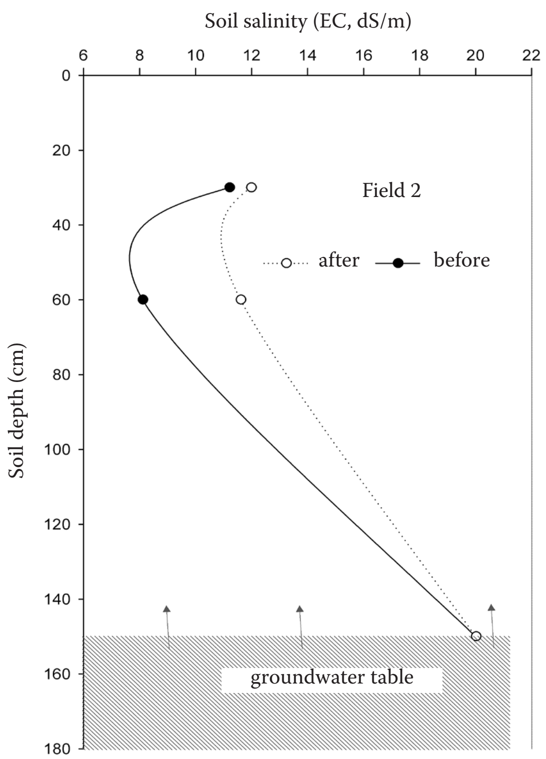

Figure 6.Leaching technique for the field with shallow groundwater table and its effect on soil salinity accumulation

For the high salinity situation of our study area, leaching combined with surface runoff flushing seems to be a promising strategy to decrease salinity problems, because flushing supports the removal of salts from the soil surface by runoff and overland flow (Ayers & Westcot 1985). If the water has not flushed the surface crusted salt, the ponding water will transport the high salinity of the topsoil to the lower profile, and this will require a prolonged leaching application, which, in turn, could raise the groundwater table rendering the treatment ineffective.

Leaching efficiency has been shown to vary with soil texture (Van Hoorn 1981). The results of our experiment show that the light (sandy loam) soil of F1, which had the highest saturated hydraulic conductivity, was more effectively and significantly reclaimed than the heavy (clay loam) soils of F2 and F3.

Several factors have been shown to influence the leaching reclamation of saline fields, including soil and irrigation water salinity levels, groundwater table of the land, irrigation application methods and time of water application (Corwin *et al.* 2007; Ayars *et al.* 2011). In addition to these main factors, we recognized in our experiment that leaching efficiency could be strongly enhanced through certain field structural conditions. For a larger-scale field application of leaching treatments with furrow irrigation, gently sloping fields and low ridge furrow depths are advantageous. During our experiment, salt was depleted exponentially after the high ridge furrow was demolished for F1 and F3, and the temporal measurements showed that the salinity level of the drainage water was very high after furrow demolishing. Meanwhile, high saline leachate management will sustain the reclaimed land. Otherwise, the leachate water brings a challenge for downstream irrigation users and high saline groundwater may rise up, as currently observed in the Awash Basin, the Gewane swampland expansions, and the growth of Lake Beseka (Gelaye *et al.* 2018).

CONCLUSIONS

In this experiment, groundwater depth was the main factor for effective leaching; soil texture also affected leaching efficiency. By the tested leaching technique with surface drainage, two of the three experimental fields were reclaimed from degraded land to marginally productive land. However, fields with shallow groundwater table showed a slight salinity increment after leaching. For shallow water table situations, subsurface drainage may be an op-

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tion for effective salt remediation. On the other hand, more effective leaching (per applied surplus water) was achieved in the field with sandy loam soil than in clay loam fields. In this case for clay loam fields with deeper groundwater, a prolonged leaching application needed. In the Kesem scheme, middle parts of the long-term irrigated fields were more affected by salt. After leaching the drainage part of the sandy loam field shows less salt than the middle and head parts. Generally, the special salt distribution of long-term irrigated fields without drainage system and leached fields with surface drainage did not show similar salinity distribution. Sustainable irrigation practice requires that the highly saline leachate water be collected through drainage systems, and either properly disposed or re-used to irrigate salt-resistant crops. This study concluded that the immediate relief of salinity-induced productivity loss by leaching and flushing techniques appears to be a very effective method in tackling irrigated agriculture constraints in Middle Awash irrigation schemes.

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