SOIL & CROP SCIENCES | RESEARCH ARTICLE

Top-soil salinity mapping using geostatistical approach in the agricultural landscape of Timuga irrigation scheme, South Tigray, Ethiopia

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Abstract: Long-term irrigation activities in arid and semi-arid areas causes soil salinity problem. Thus, knowing soil salinity status is a prerequisite for designing appropriate irrigation management strategies. This study was therefore conducted to predict top-soil salinity of Timuga irrigation scheme and to map its spatial distribution using geostatistical techniques. An area of 33.5 km² was delineated, and regularly spaced grid (cell size: 500 m) of sampling points were generated using fishnet of the ArcGIS 10.2. A total of 106 composite soil samples were collected from each sampling points at a depth of 20 cm and geo-referenced using global positioning system. Soil samples were analyzed for pH, electrical conductivity (ECe), cation exchange capacity, and exchangeable bases (Ca²⁺, Mg²⁺, K⁺, and Na⁺) following the standard laboratory procedure. Both descriptive statistics and ordinary kriging interpolation techniques were used to analyze the data. The result showed that electrical conductivity ranged from 0.125 to 12.89 mS cm⁻¹ and the exchangeable sodium percentage ranged from 0.094% to 27.514%. This indicated that soils of the irrigation scheme are characterized by saline and sodic soils with different degree of spatial variability. The total area of 75.3% and 24.7% has classified as low and medium salinity hazards, respectively. However, 3.11%, 76%, and 20.89% of the total area have classified as high, medium, and low sodicity hazards, respectively.

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PUBLIC INTEREST STATEMENT

The local communities in Timuga irrigation scheme, southern zone of Tigray, Ethiopia, have been engaged in traditional and modern irrigation practices for a long period of time. However, as the area is characterized by arid and semi-arid climatic conditions, there is a possibility of happening soil salinity in the irrigated land of Timuga agricultural landscape. Knowing the status of soil salinity and providing best management options to the local community are found to be very important for sustainable irrigation management. Accordingly, soil samples were collected and analyzed for salinity indicators following the standard laboratory procedure. The data analysis result indicated that salinity hazard is existed in the irrigated land and is building up gradually with the expansion of irrigation. Hence, the local community in collaboration with the local government needs to monitor and manage soil salinity of the irrigation scheme in order to sustain irrigation productivity.
levels, respectively. Therefore, it was concluded that soil salinity hazard is existed and is building up of gradually in parallel with irrigation expansion. Hence, prevention and recovery measures are needed considering a variety of options such as leaching, fertilization, and planting salinity-resistant crop varieties to sustain irrigation productivity.

Subjects: Agriculture & Environmental Sciences; Soil Sciences; Geographic Information Systems; Remote Sensing

Keywords: Geostatistical approach; irrigation scheme; soil salinity; spatial interpolation

1. Introduction

Soil salinity is one of the main environmental degradations throughout the world. Soil salinity is termed as the occurrence of much more accumulation of soluble salts around the active root zone (Foth, 1990). Soil salinity affects growth of plants by the osmotic pressure created within the plants, which delay the plant roots to take water smoothly (Corwin & Lesch, 2003). The concentration of salts in soil solution can also limit plant growth by creating toxicity or nutrient imbalance in the root zone (Tester & Davenport, 2003). Many researchers around the globe have documented their findings on the negative impact of soil salinity on physiological and metabolic activities of most agricultural crops (Asfaw, Suryabhagavan, & Argaw, 2018; Jouyban, 2012; Mensah, Akomeah, Ikhajiagbe, & Ekpekurede, 2006; Nasri, Saïdi, Kaddour, & Lachaâl, 2015). Soil salinity can be created either from rock and mineral weathering or from buildup of salts as a result of irrigation under poor drainage (Chhabra, 2017). Soil salinity by now is becoming an international problem in many of the irrigated lands, which have inadequate drainage and use too much amount of irrigation water. Globally, FAO (1990) estimated that about 20–30 million hectares of land are badly affected by salinity. Degradation of a land attributed to soil salinity problem became major threats to small-scale agriculture in Africa. It has been reported that about 1,899 million hectares of the African land are affected by salinity (Paul & Lade, 2014). Ethiopia, one of the East African countries, has comparable challenges in soil salinity, and about 44 million hectares of its land are estimated to be potentially susceptible to soil salinity problem (Hawando, 1997). Majority of the land that is affected by salinity and sodicity in Ethiopia have reported to happen in the areas of rift valley zone (Abebe, Alamirew, & Abegaz, 2015; Seid & Genanew, 2013; Taddese & Bekele, 1996). Soil salinity is a predominant environmental hazard in arid and semi-arid regions around the globe (Alibed & Kumar, 2013; Hillel, 2000). This is due to the ever-changing climatic condition, substantial evapotranspiration rates, shortage of water for leaching, and poor irrigation water quality (Abdelfattah, Shahid, & Othman, 2005; Jouyban, 2012).

Due to its arid and semi-arid climatic condition, soils of the Tigray region are vulnerable to salinity. Kebede (2009) stated that there is a rapid increase in soil salinity in the irrigated fields of Mekelle Plateau, Tigray. However, the regional government has still a need to expand large and small-scale irrigation agriculture to increase agricultural productivity (Mamo, Richter, & Heiligatag, 1996). Annual report of the BoARD (2015) indicated that, to date, a total of 213,941 ha of land is under irrigation, and the regional government has an ambitious plan to expand irrigation development throughout the region.

Timuga irrigation scheme, which is situated in southern zone of Tigray region, is one of the irrigation schemes of the region covered an area of 33.5 km². The local communities have been engaged in irrigation activities traditionally for a long period of time using surface irrigation water. Moreover, the scheme has been nominated by the regional government to be a development corridor and much more governmental and private agricultural investments are being performed. There are about 30 functional boreholes built recently by the regional government for the purpose of modern irrigation expansion. The communities are now producing market-oriented field crops twice or more per a year.
It is hypothesized that the irrigation scheme could be affected by soil salinity and substantially limit crop yields as a result of the continuous irrigation practices implemented by the development practitioners.

The mechanism for soil salinity in the irrigation scheme was assumed as the result of the significant amounts of ground water pumped from boreholes and flooded without proper irrigation management such as inadequate drainage and insufficient water for leaching; the high evapotranspiration rate of the arid and semi-arid climatic condition of the area; and the limited amount of rainfall for leaching.

Hence, it is expected that the implementation of intensive irrigation practices in this irrigation scheme can be resulted in a gradual accumulation of salts and decreasing agricultural production. Studies demonstrated that continuous irrigation practices would affect agricultural production potential through salt accumulation in irrigated fields (Zewdu, Suryabhagavan, & Balakrishnan, 2017).

However, no one has been studied whether the irrigation scheme is saline soils or not. The objective of this study was, therefore, intended to predict top-soil salinity status across the agricultural landscape of Timuga irrigation scheme and to map its spatial distribution through a geostatistical approach.

2. Materials and methods

2.1. Study area

Timuga irrigation scheme is located in southern zone of Tigray regional state, which is 15 km south of Alamata town (Figure 1). It is found between 12°16′ and 12°20′ latitudes and 39°34′ and 39°55′ longitudes. Timuga irrigation scheme is believed as one part of the Ethiopian rift valley (Hagos, 2010). It covers an area of 33.5 km².

The average altitude of the irrigation scheme is 1439 m above sea level. It is dominated by alluvial soils deposited from sediments coming from the mountains which bounds in east direction. It has a semi-arid climatic condition with an average annual rainfall of 724 mm. The irrigation scheme has a bi-modal pattern of rainfall with short rain season what they call “Belg” which showers from March to April and a long rainy season called “Kiremt” which falls from July to September.

2.2. Soil sampling design

An area of 33.5 km² irrigation scheme was demarcated using a Google earth and created a polygon layer for being studied. Grid sampling, one of the soil sampling strategies which deliver more in-depth information about spatial distribution of soil salinity (Carter & Gregorich, 2008; Jones Jr, 2001; Soil Survey Staff, 2014), was used for this study. Fishnet tool of the ArcGIS 10.2 software was used to generate a regularly spaced grid of sampling points inside the polygon layer. The grid cell size was made to be 500 m, and a composite soil samples were collected from each grid node. Each composite soil sample was composed of nine subsamples that were collected at a distance of 15 m radius around the center of sampling point. The coordinates of each composite soil sampling points were recorded using a global positioning system at an accuracy of ±3 m. Sampling depth was decided based on depth of soil mixing for land preparation and depth of majority of root crops growing or potentially to be grown in the irrigation scheme (Jones, 2001; Soil Survey Staff, 2014). Consequently, the subsamples were collected from the surface soil (0–20 cm) using a hand auger. The collected subsamples were put in a clean plastic tray, crushed, mixed thoroughly, and transferred 1 kg composite soil sample to plastic sampling bag. A total of 106 composite soil samples were collected from the delineated irrigation scheme (Figure 2). Finally, all soil samples were transported to Mekelle soil, plant, and water sample analytical laboratory for analysis.
Figure 1. Location map of the study area.

Figure 2. Soil sampling locations.
2.3. Soil sample analysis
Field soil samples were air-dried at a convenient laboratory temperature (24°C) timely to reduce soil mineralization (Jones, 2001; Ryan, Estefan, & Rashid, 2007). Following the drying process, soil samples were ground mechanically by using mortar and pestle and then passed through a 2-mm mesh sieve to be ready for laboratory analysis. pH of the soil was determined by preparing soil water solution at the ratio of 1:2.5 (ISRIC, 1992; Jones, 2001; Okalebo, Gathua, & Woomer, 2002; Ryan et al., 2007). Soil pH was then measured by inserting the electrodes of the pH meter into the soil suspension following its calibration. Saturated paste method (Jones Jr, 2001; Rhoades, Chanduvi, & Lesch, 1999) at soil water ratio 1:1 was used and then measured the electrical conductivity (ECe) using digital conductivity meter. The cation exchange capacity (CEC), the measure of the amount of readily exchangeable cations in the soil, was determined by ammonium acetate method at pH of 7.0 following the procedure outlined in Chapman (1965). To determine the major exchangeable cations (Ca, Mg, Na, and K), soil samples were extracted by using ammonium acetate method at pH of 7.0 (ISRIC, 1992; Jones Jr, 2001; Okalebo et al., 2002). The amount of sodium and potassium in the extract were measured by flame photometry, whereas the amount of calcium and magnesium were measured by absorption spectrophotometry. The exchangeable sodium percentage (ESP), the widely used means of soil sodicity measurement, was estimated using Equation (1) (Horneck, Ellsworth, Hopkins, Sullivan, & Stevens, 2007; McNeal & Coleman, 1966; Sposito & LeVesque, 1985; Thomas, Dalal, & Standley, 2007).

\[
ESP = \frac{\text{Exchangeable sodium}}{\text{Cation exchange capacity}} \times 100\%
\]

where exchangeable sodium and CEC are in meq 100 g\(^{-1}\). Finally, soil salinity classes were determined based on the limit established by Richards (1954).
2.4. Data analysis

Descriptive statistical parameters such as minimum, maximum, mean, standard deviation, and coefficient of variation (CV) were used to analyze soil property data. As the descriptive statistical approaches overlook spatial variability among observations (Nanos, Grigoratos, Martín, & Samara, 2015; Nourzadeh, Hashemy, Rodríguez Martín, Bahrami, & Moshashaei, 2013), geostatistical techniques have been used to analyze spatial distribution of soil properties (Goovaerts; López-Granados, Jurado-Expósito, Pena-Barragan, & García-Torres, 2005). Geostatistics has been widely used to estimate and map soil properties across spaces. Kriging is one of the exact methods of geostatistics (Lam, 1983) used widely in many disciplines including soils (Goovaerts; Li & Heap, 2011). Among the kriging algorithms, ordinary kriging (OK) that is suitable spatial prediction models for geostatistical analysis of environmental variables (Hengl, 2007), such as soil properties (Bernardi et al., 2017; Goovaerts; Nezami & Alipour, 2012; Walter, McBratney, & Douaoui, 2001) was used to predict top-soil salinity status over the irrigation scheme. OK is a univariate interpolation techniques used extensively in soil science applications (Burgess & Webster, 1980). The OK technique depends on weighting scheme where closer sample locations have greater impact on the final prediction (Bishop & McBratney, 2001). The OK model is important in predicting each value of soil salinity parameters on un-sampled locations of the agricultural field based on the spatial pattern of the collected and analyzed soil salinity data. The semi-variogram model found from the semi-variance analysis was used to estimate the values of soil salinity parameters in the un-sampled locations within the study area. The variogram is subsequently used for constructing the OK models. In our case, soil salinity indicators (pH, EC, and ESP) were mapped by OK and created as raster layers in ArcGIS 10.2 environment. Finally, the generated raster layers of each soil parameter were further reclassified in spatial analyst tools of the ArcGIS 10.2 software using different salinity classes (Horneck et al., 2007; Marx, Hart, & Stevens, 1996; Tekalign, Haque, & Aduayi, 1991). The overall work flow is depicted in figure 3.

3. Results and discussion

3.1. Soil resection (pH)

Soil pH of the study area ranged from 7.65 to 10.5 with a mean of 8.7 and CV of 4.8% (Table 1). According to soil alkalinity rating fixed by Tekalign et al. (1991), soils of the irrigation scheme varied from moderate alkaline soil to strongly alkaline soils. One percent of the total soil samples were classified as moderate alkaline soils, whereas 99% of the soil samples were classified as strongly alkaline soils.

The geospatial analysis result showed that (Figure 4) 85.7% of the total irrigated land is characterized by strongly alkaline soils, whereas 14.3% is characterized by moderately alkaline soils.

The low CV of 4.8% (Table 1) approved the similarity of soil pH values over the study area. The vast majority of the irrigated land (85.7%) has pH value greater than 8.5, and small portion of the land (14.3%) has pH value 7.5–8.5 (Table 2). This showed that the study area is dominated by strongly alkaline soils. The result is in consistence with the preliminary expectation that the irrigation scheme could be alkaline soils. A similar result of strongly alkaline

| Table 1. Descriptive statistics of soil pH, EC, and ESP |
|-----------------------------------|---|---|---|---|---|
| Parameter | Min | Max | Mean | SD | CV (%) |
| Soil pH    | 7.65 | 10.5 | 8.7 | 0.42 | 4.8 |
| EC (mScm⁻¹) | 0.125 | 12.89 | 0.76 | 1.46 | 192.1 |
| ESP (%)    | 0.094 | 27.514 | 7.67 | 7.17 | 93.48 |
soil was gained by Seid and Genanew (2013) in the irrigated fields of Awash River Basin, Ethiopia.

This is due to the continuous irrigation practices happened in the area. This result is supported by the findings of Chhabra (2017) that irrigation water is the cause of alkalinity in arid and semi-arid regions. In such circumstances, it is needed to be alert in monitoring salinity and sodicity of the irrigation scheme (Horneck et al., 2007). The alkaline nature of the soil of the irrigation scheme can affect plant growth through unavailability of plant nutrients. For instance, in strongly alkaline soils like Timuga irrigation scheme, nitrogen availability is low due to unfavorable environment for soil microbes to mineralize and fix nitrogen (Foth, 1990). Calcium-bounded phosphorous also dominantly found in alkaline soils (Fageria, 2016). Moreover, boron, iron, manganese, copper, and zinc become insoluble (fixed) and unavailable in alkaline soils (Foth, 1990). Hence, the irrigation scheme needs fertilization with appropriate nutrients to overwhelming the deficiencies or selecting crop varieties that grow best on alkaline soils.

### 3.2. Salt concentration (ECe)

The electrical conductivity (ECe) of soil samples analyzed ranged from 0.125 to 12.89 mScm$^{-1}$ with an average value of 0.76 mScm$^{-1}$ (Table 1). According to the limit set by Marx et al. (1996), 88% of the total samples were classified as low, 7% of the samples were classified as medium, and 5% of the samples were classified as strong saline soils. The geospatial interpolation result depicted that (Figure 5) the study area is characterized by low to medium salinity level.

The high CV of 192.1% (Table 1) ratifies the variations of the EC values over the study area. The vast majority of the scheme (75.3%) (Table 3) is classified under low levels of salinity risk, whereas 24.7% of the total area is classified under medium salinity hazards (Horneck et al., 2007).
This result is devoted some a little bit from the preliminary expectation that small part of the irrigation scheme is with moderate salinity. Spatially, salinity hazards existed in the middle of the agricultural landscape where traditional irrigation practices have been executed for long period of time using shallow ground water. This result is in line with the findings of Tsige, Gebresellasie and Mamo (2000) and Shegena Zewdu, Suryabhagavan, and Balakrishnan (2017) that the irrigated fields of their study areas were affected partly by salinity, and the distribution was associated with shallow ground water. Very similar result was also reported by Asfaw et al. (2018) that 18.8% and 23% of the total area were found moderately and slightly saline, respectively. The long-term irrigation practice using shallow ground water accumulates salts on the surface of the middle catchment that are distributed around the root zone (Chhabra, 1996). This is because irrigation water can bring slowly additional salts by losing water through evapotranspiration and concentrating the dissolved salts in soil solution (Gupta & Abrol, 1990). Saline soils frequently have visible salt deposits on the surface of a soil (Horneck et al., 2007). This is happening now in Timuga.

Table 3: Relative risk of soil salinity and area coverage

| Salinity class | Area (km²) | Area (%) | Risk level |
|----------------|------------|----------|------------|
| <0.75          | 28.23      | 75.3     | Low        |
| 0.75–2         | 8.27       | 24.7     | Medium     |
| Total          | 33.5       | 100      |            |

Table 4: Relative risk of soil sodicity and area coverage

| ESP value | Area (km²) | Area (%) | Risk level |
|-----------|------------|----------|------------|
| <5%       | 7          | 20.89    | Low        |
| 5–15%     | 25.5       | 76       | Medium     |
| >15       | 1          | 3.11     | High       |
| Total     | 33.5       | 100      |            |
irrigation scheme. Figure 6 shows salt deposits on the surface of the soil of middle catchment where irrigation has been performed traditionally for a period of time.

This result is supported by the finding of Yang, Liu, Yang, Sun, and Beazley (2009) that human-induced irrigation activities influence spatial variability of salinity. As the salinity hazards are expanding in parallel with irrigation area coverage, large part of the agricultural landscape will be in danger of salinity hazard by the next couple of years. Eyasu (2005) and Bekele, Tadesse, and Konka (2012) who studied in similar sites have also stated their fear on the gradual development of salinity, unless corrective measures are implemented. The land management strategies for the irrigation scheme, as well as for rain fed of the surrounding area, should consider salinity prevention mechanisms because salinity is one of the environmental stresses in the arid land that is impacting on development, growth, yield, and quality of crops (Cullu, 2003; Jouyban, 2012). A study conducted by Haileselasie and Teferii (2012) pointed out that salinity affects land race on water uptake, % of germination, and length of root and shoot. Hence, it is mandatory to monitor salinity of the irrigation scheme through application of gypsum and limestone (Mosley, Cook, & Fitzpatrick, 2017) or planting salinity-resistant crop varieties (Mensah et al., 2006; Sohrabi, Ebadi, Jalali, & Salami, 2017).

3.3. Exchangeable sodium percentage
The values of the ESP ranged from 0.094% to 27.514% with a mean of 7.67% (Table 1). According to Richards (1969) sodicity classification, 4% of the total soil samples were found to be with ESP above 15%, whereas 96% of the total soil samples were found to be with ESP values of below 15%. In terms of risks, 4% (>15%) of the soil samples were with high risk, 15% of soil samples (5-15%) were with medium risk, and 81% of soil samples (<5%) were found to be with low risk (Horneck et al., 2007). The spatial interpolation result (Figure 7) indicated that the area is dominated by soil sodicity of low to medium risk (Horneck et al., 2007). 3.11%, 76% and 20.89% (Table 4) of the total irrigated land is classified under high (ESP>15%), medium (ESP=5-15%) and low (ESP<5%) respectively.

ESP showed the highest CV of 93.48, indicating that there is high variation over the whole irrigation scheme. The irrigation scheme is dominated by low sodium hazards. High sodicity problem was observed at very small part of the agricultural landscape. This finding was deviated from the preliminary expectation that only 4% and 15% of soil samples were found with high and medium risks.
However, this result is in line with the result of Kebede (2008) that soils of the irrigated field of Mekelle Plateau had symptoms of sodicity, and sodium hazard is emerging dangerously. However, it contradicted with the findings of Chekol and Mnalku (2012) that there was sodic soils due to high concentration of sodium in other part of the region. The probable reason for sodicity at the center of the catchment is that it has been irrigated for many years and there is by nature water logging problems as compared to the other parts of the catchment. Due to annual variation of the water table, much of the calcium and magnesium might have precipitated having behind the sodium to accumulate (Richards, 1969).

4. Conclusion and recommendations
The OK model, one of the widely known geostatistical techniques, was used to predict the values of soil salinity over un-sampling areas of the field. The semi-variogram model obtained from the semi-variance analysis used to estimate the values of soil salinity parameters in the un-sampled locations within the study area, and a raster layer of soil salinity map was generated using the OK model. The ordinary kriged map showed that the agricultural landscape of Timuga irrigation scheme is characterized by a range of salinity levels based on soil chemical properties accounting for pH, electrical conductivity (ECe), and ESP. They are classified as non-affected, saline, and sodic soils each of with different degrees of salinity/sodicity. The total area of 75.3% is classified under low levels of salinity risk, whereas 24.7% of the total area is classified under medium salinity hazards. The total areas of 3.11%, 76%, and 20.89% have classified as high, medium, and low sodicity levels, respectively. Therefore, this study pointed out that in soils of the irrigated fields of Timuga irrigation scheme, there is salinity hazard and is building up gradually as the irrigation practices are continuing. Increasing salinity hazards in the soils with this pace will cause toxicity and eventually will impair the growth of irrigated crops. Hence, reclamation measures should be introduced to soils of the irrigated fields considering series of options starting from leaching, fertilization, and selecting salinity-resistant crop varieties. This implies that appropriate management strategies should be adopted to realize the optimum production capacity of the soil.
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Competing Interest
No conflicts of interests were declared.

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