Article

The Effect of Soil Texture on the Conversion Factor of 1:5 Soil/Water Extract Electrical Conductivity ($EC_{1:5}$) to Soil Saturated Paste Extract Electrical Conductivity (EC_e)

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Abstract: The electrical conductivity of soil saturated paste extract (EC_e) is used as an indicator for estimating soil salinity. This method is time consuming and laborious and therefore, easier and faster methods are usually used with different soil/water ratios, such as 1:5 ($EC_{1:5}$), for estimating the EC_e . Usually, the relationship between EC_e and $EC_{1:5}$ is described by a simple linear empirical equation. The value of the conversion factor (CF) of $EC_{1:5}$ to EC_e is affected by the particular characteristics of the soil, such as its texture. The objective of this study is to investigate models that allow the inclusion of soil texture in the calculation of the CF , in order to improve the prediction of the EC_e . A total of 148 soil samples with different soil texture and salinity levels were selected from three regions of Greece, and EC_e , $EC_{1:5}$, as well as clay and sand contents were determined. The results show that the CF can be estimated from an equation which incorporates the clay and sand contents through the soil saturation percentage (SP) and can give a fairly good prediction of EC_e from $EC_{1:5}$ ($R^2 = 0.9887$ and $RMSE = 1.39 \text{ dSm}^{-1}$).

Keywords: soil salinity; electrical conductivity; saturated paste extract; clay; sand

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1. Introduction

Soil salinity is now one of the most important limiting factors in food production due to its impact on the degradation of soils, especially in arid and semi-arid regions. It is estimated that, worldwide, approximately one billion hectares have salinity problems [1]. Nowadays, the intensity of these problems become even greater by both the increase of the irrigated areas and the consequent increase of groundwater for irrigation in arid and semi-arid areas. Especially in coastal areas, the quality of irrigation water is degraded in aquifers. Therefore, the monitoring and evaluation of soil salinity is of vital importance for the rational management of degraded soils and sustainable food production.

Soil salinity is conventionally estimated by measurement of the soil-saturated paste extract's electrical conductivity (EC_e) [2]. Saline soils are characterized by high concentration of soluble salts and therefore by high EC_e values ($EC_e > 4 \text{ dSm}^{-1}$), while sodic soils are characterized by the composition of soluble salts with higher proportion of Na relative to Ca and Mg. Specifically, soils are classified as saline soils when $EC_e > 4 \text{ dSm}^{-1}$ and the exchangeable sodium percentage $ESP < 15\%$ and classified as sodic soils when $EC_e < 4 \text{ dSm}^{-1}$ and $ESP > 15\%$. However, it is worth noting that the preparation of the soil-saturated paste is a laborious and time-consuming process, especially in the case of clay soils where the extract collection takes longer than four hours. Thus, in the case of soil salinity mapping at field scale where the collection of many soil samples is required, the laboratory work for the measurement of EC_e becomes very difficult and intensive [3].

For these reasons, many researchers have suggested easier methods to determine EC_e in various soil-over-water extract mass ratios instead of determining EC_e . The most widely used soil-over-water mass ratios (soil:water) are 1:1 ($EC_{1:1}$) and 1:5 ($EC_{1:5}$). The 1:5 method is mainly applied in Australia and China, while the 1:1 method is used in the USA [4–6]. These methods are easier to handle due to the fixed water amount used, require shorter time for preparation and extraction, and have lower costs than the EC_e .

Many researchers have proposed different empirical linear relationships between EC_e and EC for various soil/water extract ratios [6–13]. In the case of the conversion of $EC_{1:5}$ to EC_e , the value of conversion factor (CF) referred by various researchers ranged from 5.05 to 11.7 [12]. The different values of CF , especially in the case of the conversion of $EC_{1:5}$ to EC_e , in the different regions, have been attributed to many factors. Among these is the soil texture, the gypsum and calcium carbonate content, the chemical composition of the soil solution, as well as the equilibration time and the preparation and extraction process of $EC_{1:5}$ determination. It has been documented that in coarse-textured soils the conversion factor has a higher value compared with fine-textured soils [7,12]. Also, the gypsum presence in soil, which has a relatively low solubility, affects the coefficients of the linear relationship, since the greater dilution that results from the 1:5 method leads to both a decrease in the concentration of certain ions and the increase in some others.

The abovementioned wide range of CF values (i.e., 5.05–11.7) makes it clear that the conversion factor derived from the data of one region cannot be used to determine another with different soil characteristics because significant errors in the EC_e prediction will occur. Therefore, it is important to develop new approaches and models that enable the quantitative incorporation of such factors which affect the CF for each area. Thus, the role of those factors on the CF could be better investigated. As already mentioned, the soil texture is one such factor.

Slavich and Petterson [14] and Gharaibeh et al. [15] presented empirical equations between the conversion factor and soil moisture at saturation (θ_{SP} grgr^{−1}) or soil saturation percentage ($SP\%$). The CF was inversely proportional to θ_{SP} or SP as given by the following equation

$$CF = m + \frac{k}{\theta_{SP}} \text{ or } CF = m + \frac{k}{SP} \quad (1)$$

where m and k are regression parameters.

The values of those parameters are $m = 2.46$ and $k = 3.03$ for soils of Australia [14], and $m = 1.054$ and $k = 283.4$ for soils of Jordan [15]. However, the soil saturation percentage can be empirically correlated with the soil texture, and consequently the SP can be used as a substitute for soil texture [15].

Slavich and Petterson [14] presented a non-linear relationship between SP and clay content from 344 soil samples and, using the range of clay content of Australian soils presented by Northcote [16], calculated the range of SP for each soil category. Then, they calculated the range of CF by applying Equation (1) and its mean value for each soil texture group. Slavich and Petterson [14] stated that using the mean value of CF for each soil texture group classified by clay percentage, the EC_e can be adequately predicted by $EC_{1:5}$. However, they pointed out that in the case of sandy soils, the EC_e prediction errors can be large enough because the value of CF changes significantly when $\theta_{SP} < 0.4$ grgr^{−1} according to Equation (1).

On the other hand, Gharaibeh et al. [15] studied 177 soil samples in the Jordan Valley and found that there was a strong negative correlation between the SP and the sand content, and a moderate to strong correlation between the SP and the clay content. Specifically, by using the multiple linear regression method, the relationship between the SP and the clay and sand content was

$$SP\% = 43.83 + 0.313 \cdot Clay\% - 0.303 \cdot Sand\% \quad (2)$$

In this way, the effect of the soil texture, through the SP parameter, can be included in the calculation of the CF when Equation (1) is used, improving the prediction of EC_e from $EC_{1:5}$ for the studied soils. Thus, the oversimplification which is observed when a universal CF is used for a region, resulting in significant EC_e prediction errors, can be overcome. From the comparison between the predicted CF values and the actual values ($EC_e/EC_{1:5}$), it seems that the model gave good predictions of CF . However, in the case of sandy soils, as in the case of Slavich and Petterson [14], the ability to make a reliable prediction was lower compared with medium and fine-textured soils.

Overall, there is an open field for further research on the effect of soil parameters on CF prediction using the method of multiple linear regression in various soil types and regions.

The objective of this study is to develop prediction models of the conversion factor (CF) using the soil texture through the SP index, to more reliably predict EC_e from $EC_{1:5}$ in the case of Greek soils and to compare these models with other ones. For this, 148 soil samples were collected from three regions of Greece and the EC_e , $EC_{1:5}$, the texture of the soils and the calcium carbonate content were measured.

2. Materials and Methods

2.1. Case Studies

Soil samples were collected from three regions of Greece, i.e., Dystos, Iria and Skala, with intensive irrigated agriculture (Figure 1).

Figure 1. Soil sample collection areas.

The cultivated area of each region is approximately 1000–1100 ha. The sampling areas are coastal with low altitude (1–15 m) and the crops are irrigated with groundwater (boreholes or wells) or water from the public irrigation network.

In Iria, soil salinity problems have appeared since the 1960's, while in Skala and Dystos these have appeared over the last two decades. The soil salinity in those regions, due to the use of low-quality irrigation water, fertilizers and intensive agriculture, is likely to increase in the coming years.

The climate of the studied areas is characterized as arid and semi-arid with warm and dry summer and mild winter. The mean annual rainfall is approximately 500 mm, in all studied areas. Approximately 70–80% of rainfall falls during the period of October–March.

Vegetables are the main crops in Iria and Dystos, while Skala is covered by citrus trees.

Two soil samplings were performed in Iria. The first one at the end of irrigation period (August) and the second one at the end of rainy period (March). Soil sample collection

from the other two areas was performed after the end of the rainy period. The sampling depth was 0–30 cm. A total of 148 soil samples were collected (20 soil samples from Skala, 43 from Dystos and 75 from Iria). After sampling, the soil samples were transported to a laboratory, air-dried and sieved by 2 mm sieve. Soil texture was determined by applying the Bouyoucos hydrometer method [17]. The CaCO_3 equivalent percentage was estimated by measuring the eluted CO_2 following the addition of HCl (calimeter Bernard method) [18].

2.2. Determination of Electrical Conductivity

The soil saturated pastes were prepared using the standard method USDA [2]. An amount of distilled water was gradually added to a 350 g air-dried soil sample by stirring until a saturation point is reached. The amount of distilled water which was added to each soil sample depends on the particular combination of soil physical attributes, such as texture, specific surface, clay content and cation exchange capacity. At saturation, the soil pastes glistened as they reflected light and flowed slightly when the plastic container was tipped. The soil pastes were left for 24 h to reach equilibrium. Then, they were placed on a Buchner funnel with a filter paper at its bottom and the extract was collected in a 250 mL bottle by applying vacuum with a vacuum pump (VACUMBRAND GMBH type MZ 2). The EC_e of extracts were measured at 25 °C using a conductivity meter (WTW, Cond 315i).

For the determination of $EC_{1:5}$, 100 mL of distilled water was added in 20 g of air-dried soil sample and the suspension was agitated in a mechanical shaker for 15 min. After that, it was allowed to stand for 1 h and was then agitated again for 5 min [2]. The suspension was placed on a Buchner funnel, and following the abovementioned process, the extract was obtained and the $EC_{1:5}$ was measured.

2.3. Statistical Analysis

Statistical analysis was performed using Statgraphics Centurion statistical package (version 17). For all tests, the significance level was set at 5%. Soil EC_e , $EC_{1:5}$, SP , clay and sand content are described by various statistical parameters, i.e., average value, standard deviation, coefficient of variation, standard error, minimum value, maximum value, coefficient of skewness and coefficient of kurtosis. Shapiro–Wilk test and graphical methods (Q–Q plots) to assess normality of the soil parameters EC_e , $EC_{1:5}$, SP , clay and sand content were used. The test revealed that SP , clay and sand content followed normal distributions, while EC_e and $EC_{1:5}$ did not follow normal distributions. In order to investigate if there were significant correlations between the variables, the Spearman correlations were computed, instead of the more common Pearson correlations, because some of the variables did not follow the normal distribution. The Spearman coefficients range from -1 to $+1$ and are computed from the ranks of the data values rather than from the values themselves. Consequently, they are less sensitive to outliers than the Pearson coefficients.

Additionally, multiple linear regression (MLR) models were used to estimate the relationship between the dependent variable SP and the independent variables clay and sand content. The coefficient of determination R^2 and the mean absolute error (MAE) were determined to evaluate the MLR models. Moreover, the assumptions of the multiple regression (linearity, normality and homoscedasticity) were checked with the help of the studentized residual plot. Studentized residuals measure how many standard deviations of each observed value of the dependent variable deviate from the fitted model using all the data except that observation. Observations that have studentized residuals greater than 3 (in absolute value) are called unusual or outliers and should be checked for their validity. Additionally, if studentized residuals are not uniformly distributed throughout the range of the predicted values of the dependent variable, the assumption of homoscedasticity is violated.

3. Results and Discussion

3.1. Soil Properties

Statistics of studied parameters of examined soil samples are presented in Table 1. From 148 soil samples examined, only 9 had SP values ranging between 30% and 40%. The rest had $SP > 40\%$ indicating that these are mainly fine-textured soils [8]. More specific, 44.5% of the samples are characterized as clay loam soils (CL), 16.2% clay (C) and 13.5% loam (L). The vast majority of CL and C soils came from Iria region. From 148 soil samples, 115 of them (77.7%) had $EC_e < 4 \text{ dSm}^{-1}$. The average value of EC_e is approx. 6.6 times higher than that one of $EC_{1:5}$.

Table 1. Statistical summary of the data on the electrical conductivity of the saturated paste extract (EC_e), electrical conductivity of the 1:5 soil/water extract ($EC_{1:5}$), soil saturation percentage (SP), clay and sand content for all soil samples.

Statistical Parameters	EC_e	$EC_{1:5}$	SP	Clay	Sand
	(dS m^{-1})	(dS m^{-1})	(%)	(%)	(%)
Average	4.01	0.61	53.98	31.53	36.12
Standard deviation	6.01	0.86	9.39	8.79	12.65
Coefficient of variation (%)	150.03	141.85	17.41	27.87	35.03
Standard error	0.49	0.07	0.77	0.72	1.04
Minimum value	0.47	0.08	30.0	7.40	3.56
Maximum value	35.80	5.77	76.84	48.50	84.60
Coefficient of skewness	3.01	3.05	−0.14	−0.11	0.63
Coefficient of kurtosis	10.34	11.19	−0.27	−0.36	1.16

3.2. Relationship between EC_e and $EC_{1:5}$

The relationship between EC_e and $EC_{1:5}$ is presented in Figure 2. Regression analysis showed that this relationship is strongly linear with $R^2 = 0.9627$ and the CF value, which is the slope of the regression line, is 6.6927. However, as shown in Table 2, the CF values change depending on the soil texture. For clay soils the mean actual value of CF is 4.72 while for sandy loam soils it is 8.22. Taking into consideration the fact that experimental CF values ($EC_e/EC_{1:5}$) vary with the soil texture, as well as how CF values of coarse-textured soils are higher than those of fine-textured soils [7,12,15], the use of a generalized value of $CF = 6.6927$ would lead to significant EC_e prediction errors. Therefore, the inclusion of the soil texture or an indicator reflecting the soil texture in the CF may improve the performance of the EC_e prediction models from $EC_{1:5}$.

Table 2. Mean values of the actual conversion factors CF ($EC_e/EC_{1:5}$) and the predicted factors based on clay and sand content (Equations (1) and (3)) for each soil type studied, and the corresponding mean relative errors.

Soil Type	Number of Soil Samples	Mean Actual CF ($EC_e/EC_{1:5}$)	Mean Predicted CF	Mean Relative Error (%)
Clay	24	4.72	5.45	15.0
Clay Loam	66	6.04	6.14	1.6
Loam	20	6.64	6.96	4.7
Sandy Clay Loam	14	6.66	7.07	6.2
Sandy Loam	9	8.22	8.17	0.5

Figure 2. Relationship between the measured electrical conductivity of saturated paste extract (EC_e) and the measured electrical conductivity of 1:5 soil/water extract ($EC_{1:5}$).

3.3. Spearman Correlation Coefficients and Multiple Linear Regression

As shown in Table 3, the EC_e is strongly correlated with $EC_{1:5}$ since the Spearman correlation coefficient is 0.942 ($p < 0.001$). Also, there is a strong positive correlation between SP and clay content with a Spearman coefficient of 0.787 ($p < 0.001$), while there is a strong negative correlation between SP and sand content with a Spearman coefficient of -0.782 ($p < 0.001$). Similar trends have been observed by Gharaibeh et al. [15]. On the contrary, there is no significant correlation between EC_e and SP (Spearman coefficient = -0.011 , $p > 0.05$), as well as between $EC_{1:5}$ and SP (Spearman coefficient = 0.150, $p > 0.05$).

Table 3. Spearman correlation coefficients among the parameters EC_e , $EC_{1:5}$, SP , clay and sand content for all soil samples.

	EC_e	$EC_{1:5}$	SP	Clay
$EC_{1:5}$	0.942 ***			
SP	-0.011	0.150		
Clay	-0.271 **	-0.115	0.787 ***	
Sand	-0.054	-0.204 *	-0.782 ***	-0.627 ***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. * Correlation was significant at the 0.05 level, ** Correlation was significant at the 0.01 level, *** Correlation was significant at the 0.001 level.

Since the SP is strongly linear correlated with clay and sand content, it may be used as a substitute of the soil texture in CF prediction. By applying a multiple linear regression model to estimate the dependent variable SP from the independent variables clay and sand content, the following equation with $R^2 = 0.749$ was obtained:

$$SP\% = 49.699 + 0.524 \cdot Clay\% - 0.339 \cdot Sand\% \quad (3)$$

The high value of R^2 means that there is significant correlation between SP and clay and sand content ($p < 0.001$) with a mean absolute error 3.703%. From Equation (3), it appears that an increase in sand content leads to a decrease in the SP value. For example, if two different textured soils are examined, e.g., a CL and a SL with sand contents 34% and 54%, respectively, and clay contents 32% and 17%, respectively, then the corresponding predicted SP values will be 54.9% and 40.3%. Comparison between the multiple linear regression Equations (2) and (3) shows a significant difference in the value of the clay

content coefficient, while the constant term and the coefficient of sand content have similar values. The difference in the clay content coefficient between the equations may be attributed to the range of the clay content of soil samples and the type of clay. Regardless of the reasons for this difference, it seems that a specific multiple regression equation must be calculated in each studied region to ensure a good *SP* prediction from the soil texture.

Figure 3 shows the relationship between the measured *SP* and the predicted *SP* (Pred*SP*) from Equation (3). It seems that the equation predicts the value of *SP* reliably since the slope of the equation is 1.0001 and the value of R^2 is very high ($R^2 = 0.9926$).

Figure 3. Relationship between the measured saturation percentage (*SP*) and the predicted saturation percentage (Pred*SP*) by Equation (3).

Figure 4 shows the studentized residual plot for the fitted model. In this case, there are 9 studentized residuals out of 148 that are greater than 2 (in absolute value), but none greater than 3. Therefore, none of the observations should be removed from the model. Additionally, we observe that most of the residuals are uniformly distributed throughout the range of the predicted values of *SP*. Consequently, we can conclude that the assumptions for linearity, normality and homoscedasticity for the proposed regression model are satisfied.

Figure 4. Studentized residual plot for the fitted multiple regression model.

3.4. Prediction of EC_e from $EC_{1:5}$ and Soil Texture

From the combination of Equations (1) and (3), the CF can be estimated from the SP using the soil texture (Equation (3)). If the coefficients m and k proposed by Gharaibeh et al. [15], i.e., $m = 1.054$ and $k = 283.4$, are used then from Table 2 it appears that the predicted values of CF are very close to the actual values. The maximum value of the mean relative error is 15% for clay soils while for the other soil types it is less than 6.2%. Thus, the EC_e can be calculated from the following equation:

$$EC_e = \left(m + \frac{k}{SP\%} \right) \cdot EC_{1:5} = \left(1.054 + \frac{283.4}{49.699 + 0.524 \cdot Clay\% - 0.339 \cdot Sand\%} \right) \cdot EC_{1:5} \quad (4)$$

As shown in Figure 5, a reliable prediction of EC_e was obtained by Equation (4) with $CF = 6.1384$ taking into consideration the measured $EC_{1:5}$ and the soil texture. The root mean square error value (RMSE) is 1.39 dSm^{-1} and $R^2 = 0.9887$.

Figure 5. Relationships between (i) the measured EC_e and $EC_{1:5}$ (Exp); and (ii) the predicted EC_e by the Equation (4) (Pred).

Therefore, from the soil data examined, it appears that Equation (4) gives reliable EC_e predictions for soils which are classified as medium to fine textured.

In the case where the coefficients of Slavich and Peterson [14] (i.e., $m = 2.46$ and $k = 3.03$) are used in Equation (4) for the prediction of EC_e , the corresponding values of R^2 and RMSE are 0.96 and 1.81 dSm^{-1} , respectively. The greater value of RMSE compared with that of Gharaibeh et al. [15] is because Equation (1), using the coefficients of Slavich and Peterson [14], gives greater values of CF for the corresponding SP values. For example, in the case of CL soils which constitute most soils in our study, when the mean value of SP for CL soils studied by Slavich and Peterson [14] (Table 1 in ref. [14]) is used, Equation (1) with the coefficients of Slavich and Peterson [14] gives a value of $CF = 8.6$, while that of Gharaibeh et al. [15] gives a value of 6.8. The mean experimental value of CF for the CL soils of our study is 6.04. It should be noted that Slavich and Peterson [14] did not use a multiple linear regression equation to predict the SP since the relationship between SP and clay content was not linear for the soils they examined.

If the simple linear regression equation (Equation (5)) to predict the EC_e is used, then the RMSE = 1.48 dSm^{-1} and $R^2 = 0.9627$

$$EC_e = 6.6927 \cdot EC_{1:5} \quad (5)$$

Overall, the *CF* prediction model of Gharaibeh et al. [15] using the *SP*, which is estimated from the soil texture, is superior to the corresponding one of Slavich and Peterson [14] in the case of medium and fine textured soils. However, it should be noted that the performance of this type of model is probably not so good in “extreme” soils, e.g., soils with high clay content or high sand content, since such soils were not included in this study. Also, these models seem to be superior compared with the oversimplified conversion models of $EC_{1:5}$ to EC_e , which, however, can lead to significant prediction errors if they are applied to other regions with different soil types.

4. Conclusions

A model was developed to predict the EC_e from $EC_{1:5}$ and *SP*, used as a substitute for soil texture, with quite reliable results for the soils studied. With this model, the conversion factor *CF* is adapted to the soil texture of the specific soil samples collection area. Since in the most cases the soil texture is known, the proposed method does not require any additional effort to calculate the *CF*.

The method is fast and reliable and could be useful in the proper management of the salinity of agricultural soils. Also, this method could facilitate the compilation of reliable salinity soil maps since the determination of $EC_{1:5}$ and soil texture is easy and fast.

It should be noted that the method presented in this study was applied using data from three regions with specific soil types. It is necessary to check the reliability of the method in other regions and soil types.

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