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Assessment of soil-water vulnerability to salinization in Ben Tre Province using DRASTIC model

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ABSTRACT

Soil water in the coastal zones is more vulnerable to salinization. Soil-water vulnerability assessment is an effective tool for soil-water management. This study used the DRASTIC model, which is based on seven factors viz: depth to soil water, recharge, soil-water bearing layer, soil media, topography, impact of root zone, and hydraulic conductivity to evaluate soil-water salinization potentiality of Ben Tre Province. The obtained soil-water vulnerability map is divided into three vulnerable zones: low vulnerability zone with 348.59 km^2 of total area, moderate vulnerability zone with 1898.77 km^2, and high vulnerability zone having 147.64 km^2. Moreover, the DRASTIC model was validated by Total dissolved solids (TDS) over the study area. Validation results showed the low vulnerability zone of the moderate saline (TDS = 1,500–7,000 mg/L), while the moderate vulnerability zone of the moderate, high, and very high saline (TDS = 1,500–35,000 mg/L). However, the high vulnerability zone has a very high saline (TDS = 15,000–35,000 mg/L). The study results are of considerable value to land use planning and soil researchers.

Keywords: Soil water, salinization, vulnerability, DRASTIC model.

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INTRODUCTION

The hydrosphere comprises all water bodies (oceans, rivers, lakes), groundwater, and soil. Soil water underlying the ground surface comprises gravity water and capillary water. Because of the gravitational force, a part of the soil water moves from the ground surface down to become gravity water; the remaining are evaporated and used by plants. The capillary water is retained in the soil by the capillary force. Compared to other water resources, soil water is more vulnerable to different pollution sources. Seawater intrusion is a primary agent that causes salinization to both groundwater and soil water [1, 2].

Ben Tre Province was heavily affected by climate change - sea level rise and upstream water reduction. In 2003, seawater intrusion became severe, especially in the dry season of years 2015–2016: salinity of 4‰ in the main rivers intruded inland up to 45–70 km; the salinity of 1‰ covered throughout the province (162/164 communes, wards, and towns). From the end of 2019, the saline intrusion into the Mekong River system began more complicated. It is predicted that the long-term reduction of rainfall associated with the exploitation of water resources of major rivers and the storage of upstream water should cause drought water shortage; therefore, the saline intrusion should become more serious compared to the dry season 2016. The observations at the beginning of 2020 showed Ham Luong River the seawater intrusion range of 71 km, about 11 km farther than in the same period in 2016; the Co Chien River - 65 km, equivalent to the same period in 2016; The Bassac River - 61 km, about 2 km farther compared with the same period in 2016 [3, 4].

The first DRASTIC model developed under the cooperation between the United States Environmental Protection Agency (USEPA) and the National Water Well Association (NWWA) was built to assess groundwater vulnerability to pollution sources by integrating seven thematic layers (factors/parameters) [5]. The DRASTIC model for groundwater susceptibility has been successfully applied in the world such as America (e.g., Canada, South America, and USA), Europe (e.g., Italy, New Zealand, and Sweden), Asia (e.g., Australia, China, India, Iran, Israel, Japan, Jordan, South Korea, Thailand, and Vietnam) and Africa (e.g., Morocco) [6–9]. The article is to apply the DRASTIC model for evaluating the soil-water vulnerability to salinization in Ben Tre Province.

MATERIAL AND METHODS

Study area

Ben Tre, one of the provinces in the Mekong Delta, Vietnam, lies between 9°48’–10°20’N and 105°57’–106°48’E long with a natural area of 2,395 km^2 (Fig. 1). Riverside and coastal low-lying regions below 1.0 m are inundated regularly during high tide. Ben Tre land in the form of a big river island in the Mekong River mouth has been formed by an alluvial deposition process with a densely interlaced river/canal/ditches system accounting for 446.02 km^2 (18.62%) of the total area, which is composed of Co Chien river, Ham Luong River, and Tien River, and a long coastline of over 65 km.

Establishment of borehole network

A network of 150 borehole points was established in the study area, with the distance between the points about 5 km to collect field data (Fig. 1). Coordinates were determined by Garmin handheld GPS map 60CSx with an accuracy of ±5 m. A point location was selected to be typical to the survey place, i.e., rice/garden land, river/canal/ditch banks. All 150 hand-augering boreholes reach a depth of 100 cm. Data collection time is from the end of 2017 to June 2018.

Data collection

Vertical electrical sounding (VES)

In VES measurement, the electrode configuration is referred to as a Wenner array when four electrodes are equidistantly spaced in a straight line at the soil surface, with the two outer electrodes serving as the current or transmission and the two inner electrodes serving as the potential or receiving electrodes. The penetration depth of the electrical current depends on the interelectrode spacing. The measurement was carried out near 150 hand-augers with AB/2 = 0.6, 1.2, 2.1, 3.0, 6.0, and 9.0 m respectively. Such a process of electrode separation is sufficient to match the required depth of investigation in the study area. From that data, the electrical properties of the earth can be derived, thereby, the geological properties inferred. The sounding curves for 4 measuring stations show that the apparent soil electrical resistivity (ρ_a) in the first logarithmic cycle (AB/2 = 0.1-1.0 m) reveals the different lithological heterogeneity of topsoil. In the second cycle (AB/2 = 1.0-10 m), they have moderate resistivity values (20–50 Ohm-m) about AB/2 = 1.0 m (Fig. 2).

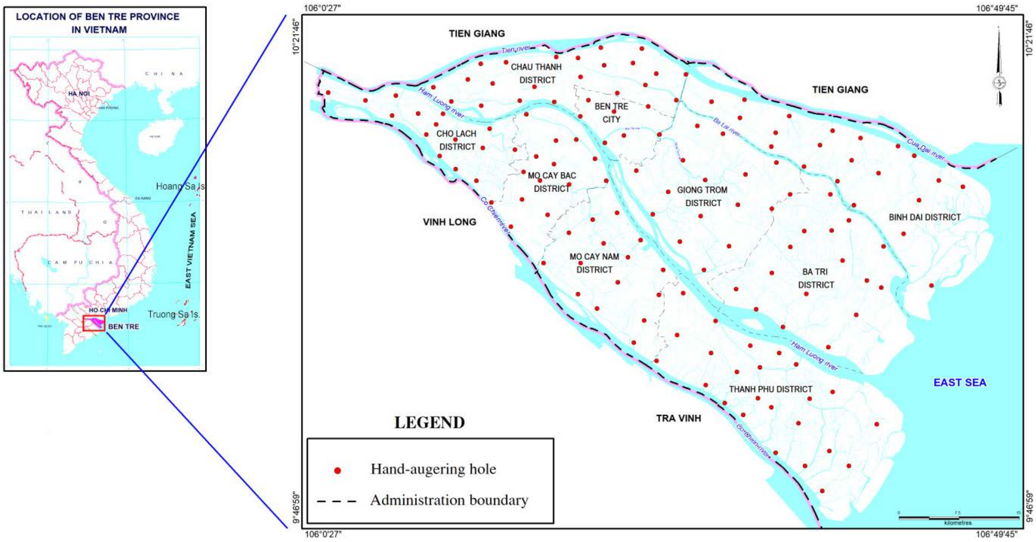

Figure 1. Study area (Ben Tre Province) and location of hand-augering holes

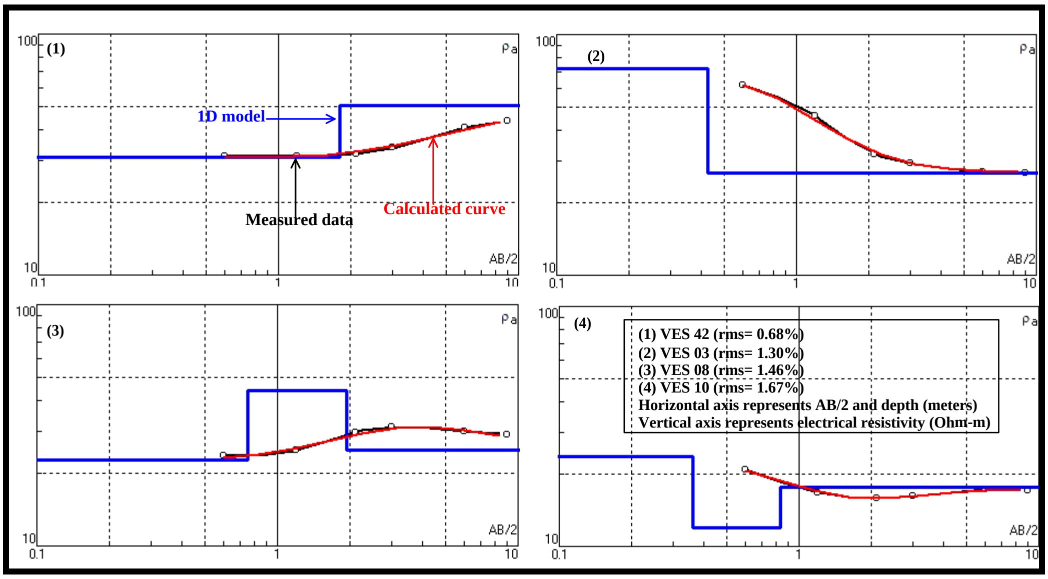

Figure 2. 1D models obtained from resistivity data inversion at VES42, VES03, VES08, and VES10

For the inversion and interpretation of the VES field data, the IPI2Win software was used. This automatic curve-matching program results in two- or three-layer geoelectric models. Fig. 2 shows four examples of the models obtained at the measuring points VES42, VES03, VES04, and VES10, in which VES data inversion (red line) exhibits a good fit with the measured data (open circles). The root mean square (rms) errors between the observed and calculated resistivity values range from 0.68% to 1.67%. The result of a VES via curve interpretation is a layered model with thicknesses (h) and actual resistivity values (ER_{bulk}) for each geoelectrical layer (Table 1). The variation in ER_{bulk} from 17.7–50.5 Ohm-m and depth to final geoelectrical layers 0.4–2.0 m, which may be attributed to the different effects of soil-water bearing layers.

Table 1. 1D models of 4 VES stations in WGS84/UTM

Station	*X* (m)	*Y* (m)	ER_{bulk1} (Ohm-m)	h_1 (m)	ER_{bulk2} (Ohm-m)	h_2 (m)	ER_{bulk3} (Ohm-m)
VES03	663028	1130952	30.7	1.8	50.5	-	-
VES08	682840	1111734	71.9	0.4	26.6	-	-
VES10	618430	1135024	22.6	0.8	43.8	1.2	25.1
VES42	664921	1122071	23.8	0.4	11.9	0.5	17.7

Soil and soil-water sampling for laboratory analysis

One hundred fifty soil samples were taken with a weight of 2 kg in a depth of 0–30 cm; 150 soil-water samples in a depth of 10–100 cm were collected with a volume of 2 liters and stored in a closed foam container at a temperature of 4^oC. The soil samples were analyzed for the grained texture; for the soil-water samples, their electrical conductivity (EC_w) was measured in field with the multi-indicator device Sper Scientific 850081 (USA); and TDS concentration was analyzed by gravity method in the laboratory [10].

Formation factor (F)

The relation between the actual conductivity value ($EC_{bulk} = 1/ER_{bulk}$) of the soil-water-bearing layer and soil-water conductivity values (EC_w) is determined by Archie's empirical formula [11, 12]:

$$EC_{bulk} = F.EC_w = a\Phi^m.EC_w \tag{1}$$

where: a is an empirical constant; Φ is the porosity; and *m* is the cementation coefficients. *F* is the so-called formation factor that depends on *a*, Φ, and m values of the soil-water bearing layer. From Formula (1), it can be determined *F* when EC_{bulk} and EC_w are measured at every hand-augering hole.

Kriging and Cokriging interpolation

Kriging interpolation was used for the spatial distribution of the measured depth of soil-water levels (*d*) and the calculated formation factor (*F*) via MapInfo 15 software.

The Kriging is a local determination method that uses the spatial dependence of a particular variable for the estimation procedure. The predictor $\mathbf{X}(s_o)$ at the space location s_o is a linear combination of the n_s observations x_1,..., x_{ns}:

$$\mathbf{X}(s_o) = \sum_{i=1}^{n_s} \lambda_1 X(s_i) \tag{2}$$

where: the n_s weights are calculated such that $X(s_o)$ is unbiased and the variance of the prediction error is minimal.

Cokriging is an extension of kriging to assess spatial correlation between two or more variables. For the more accurate estimates, cokriging can be used to estimate a missing observation at a given time instant by considering the observations at this time instant as the variable of interest and the observations at other time instants. The kriging estimator of $\mathbf{X}_2$ at an unsampled location s_o is:

$$\mathbf{X}_2\left(s_o\right)\sum_{i=1}^{n_1}\lambda_{1i}X_1\left(s_i\right)+\sum_{j=1}^{n_2}\lambda_{2j}X_2\left(s_j\right) \quad (3)$$

with λ_{1i} and λ_{2j} are the kriging weights relative to the variables $\mathbf{X}_1$ and $\mathbf{X}_2$, respectively. When $\mathbf{X}_1 = \mathbf{X}_2$ cokriging system (3) becomes kriging (2).

DRASTIC model

At first, the DRASTIC model aims to evaluate the potential of groundwater pollution by considering seven hydrogeological parameters, i.e., groundwater depth (D), recharge (R), aquifer (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C) [5]. These seven factors are assigned weights from 1 (least important) to 5 (most important) according to their ability to reduce the infiltration of contaminants. The DRASTIC index (D_i) produced from the summation of the seven hydrogeological factors is represented by the following Equation (4):

$$D_i = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \quad (4)$$

where: r is the rating; and *w* is the weight.

In the case of applying the DRASTIC model for soil water, it should be assumed that some hydrogeological parameters will be appropriately changed, i.e., depth to groundwater is replaced by depth to soil water; aquifer by soil-water bearing layer, and impact of the vadose zone by impact of the root zone. Besides, the weights of two factors, topography and hydraulic conductivity, are assigned to 2 and 4 instead of 1 and 3, respectively (Table 2).

Table 2. Factors and weights in DRASTIC models for groundwater and soil water

DRASTIC model			
Groundwater		Soil water	
Factor	*Weight*	*Factor*	*Weight*
Depth to groundwater	5	*Depth to soil water*	5
Recharge	4	Recharge	4
Aquifer	3	*Soil-water bearing layer*	3
Soil media	2	Soil media	2
Topography	*1*	Topography	*2*
Impact of vadose zone	5	*Impact of root zone*	5
Hydraulic conductivity	*3*	Hydraulic conductivity	*4*

DRASTIC model factors

In the DRASTIC model, a rating varies from 1 to 10 while a weight - from 1 to 5. They are multiplied by each other and then summed up to get the DRASTIC index (Table 3). The final vulnerability map is obtained with seven factors using ArcGIS 9.2 software.

Depth to soil water

Refers to the thickness of the root zone through which saline water can infiltrate down to the soil-water-bearing layer. The shallower the depth, the higher the salinization possibility. Depths to soil-water level at 150 boreholes vary between 10 cm and 30 cm (Fig. 3a).

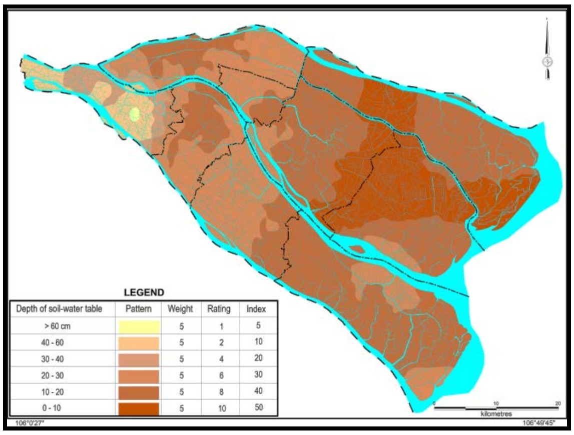

Figure 3a. Depth to soil water

Recharge

Represents the water that penetrates the ground surface and reaches the soil-water level. Usually, the more the net recharge, the higher the salinization possibility. However, in this case, the seawater intrusion could occur laterally from the sea and river/canal/ditch water; therefore, the soil-water salinization is reduced when the net recharge increases. The following relation was used to map the net recharge (Fig. 3b).

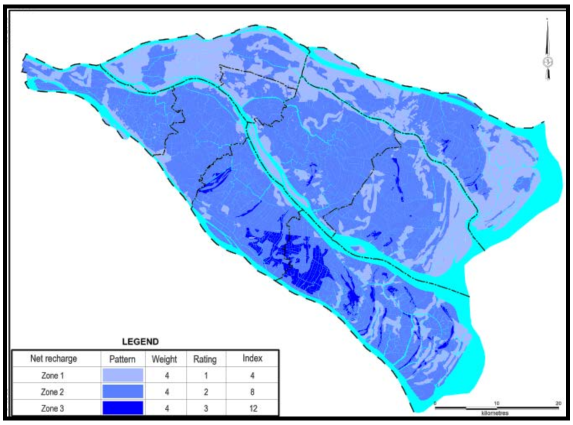

Figure 3b. Recharge

Amount of water = soil permeability + rainfall + slope

Soil-water bearing layer

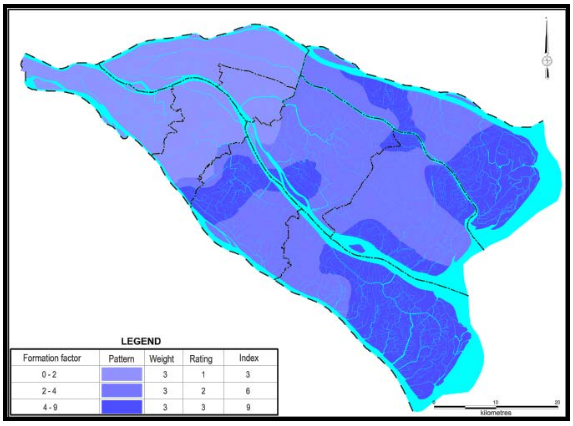

Figure 3c. Formation factor

Refers to the soil-water bearing layer material properties that control the salinity attention. As presented above, because the formation factor (F) depends on the soil-water bearing layer's porosity, it is used to map for this factor. The greater the formation factor, the higher the salinization possibility (Fig. 3c).

Soil media

The soil media is the uppermost part of the unsaturated zone that affects the salinization ability to move within the soil down to soil water. A soil map at scale 1:50,000 of the study area was used to group the soil types (Fig. 3d).

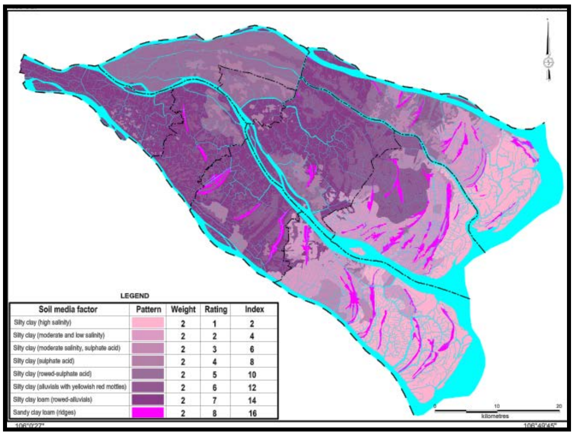

Figure 3d. Soil media

Topography

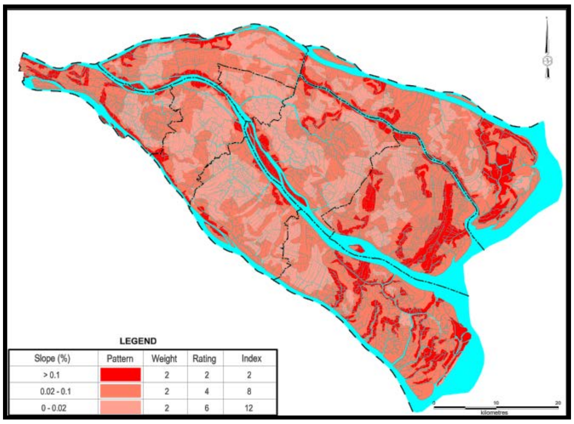

Figure 3e. Slope

The topography refers to the slope of the ground surface of the study area. The smaller the slope, the higher the soil-water salinization possibility. A topography map at a scale of

1:50,000 was used to produce the slope map (Fig. 3e).

Impact of the root zone

The unsaturated zone materials control the passage and attenuation of saline water into the soil-water bearing layer. Analysis of 150 soil samples was carried out, of which the lithological composition includes sand, silt, and clay to prepare the root zone map (Fig. 3f).

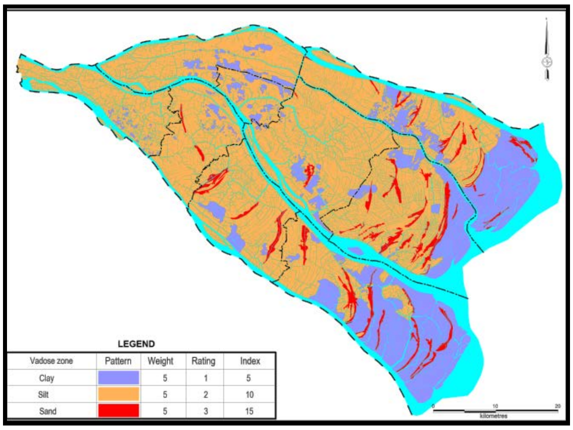

Figure 3f. Impact of root zone

Hydraulic conductivity

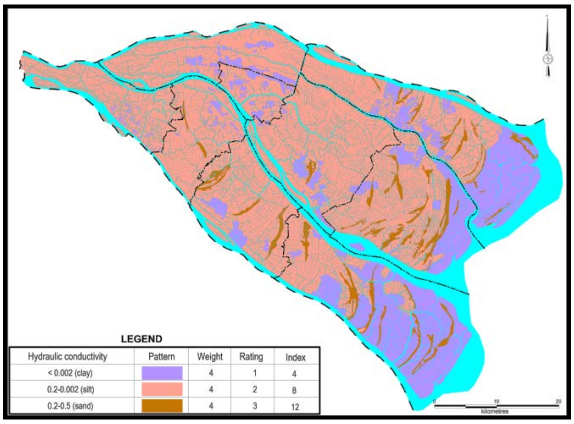

Figure 3g. Hydraulic conductivity

Indicates the ability of water transmission, hence determining the rate of salinization in the soil-water bearing layer. The greater the hydraulic conductivity, the higher the salinization possibility. To map the hydraulic conductivity, the grained-texture of 150 soil samples was analyzed and classified according to Ritzema H.P. [13], namely sand (0.2–0.5 m/day), silt (0.2–0.002 m/day) and clay (< 0.002 m/day) (Fig. 3g).

RESULTS AND DISCUSSION

Equation (4) with seven factors from 1 to 7 of Table 3 are used to obtain the map of soil-water vulnerability to salinization (Fig. 4). The range of the DRASTIC vulnerability index in this study is between 36 and 128. These values are reclassified into low, moderate, and highly vulnerable zones. According to the results of the soil-water vulnerability assessment, the study area can be divided into three zones: low soil-water vulnerability zone (index 36–72), moderate soil-water vulnerability zone (72–104), and high soil-water vulnerability zone (104–128). The DRASTIC soil-water vulnerability map (Fig. 4) shows the predominant moderate vulnerability class in most of the Ben Tre province, occupying an area of 79.28%. The low soil-water vulnerability class occupies an area of 14.55% and is located northwest of the study area. The zones with high vulnerability occupy only 6.17% of the total area.

The reasons for such low vulnerability, especially in the northwest part of Ben Tre province, are occupied by soil with low permeability and a greater depth to soil water (> 60 cm). The zones with high vulnerability are distributed mainly into the small zones in the central part of the study area. The high vulnerability in these zones is probably related to the shallowness of the soil-water level (< 10 cm), the high infiltration rate and the relatively high permeability of the root zone materials, mainly silt. The zones with moderate vulnerability cover the rest of the study area, characterized by a deeper soil-water level (10–60 cm), relatively low recharge (Zone 2) and soil with low permeability.

The soil-water vulnerability map was validated with TDS in soil water as shown in Fig. 5. Results of validation show the low vulnerability zone of the moderate saline (TDS = 1,500–7,000 mg/L), while the moderate vulnerability zone of the moderate, high, and very high saline (TDS = 1,500–35,000 mg/L). However, the high vulnerability zone has a very high saline (TDS = 15,000–35,000 mg/L).

Table 3. DRASTIC factors used for study

Factor	Weight	Rating	DRASTIC index
Depth to soil water (cm)			
0–10	5	10	50
10–20		8	40
20–30		6	30
30–40		4	20
40–60		2	10
> 60		1	5
Recharge			
Zone 1	4	1	4
Zone 2		2	8
Zone 3		3	12
Soil-water bearing layer (Formation factor F)			
0–2	3	1	3
2–4		2	6
> 4		3	9
Soil media			
Silty clay (high salinity)	2	1	2
Silty clay (moderate and low salinity)		2	4
Silty clay (moderate salinity, sulphate acid)		3	6
Silty clay (sulphate acid)		4	8
Silty clay (rowed-sulphate acid)		5	10
Silty clay (alluvial with yellowish red mottles)		6	12
Silty clay loam (rowed-alluvial)		7	14 16
Sandy clay loam (ridges)		8	
Topography (slope%)			
0–0.02	2	3	6
0.02–0.1		2	4
> 0.1		1	2
Impact of root zone			
Sand	5	3	15
Silt		2	10
Clay		1	5
Hydraulic conductivity (m/day)			
0.2–0.5 (sand)	4	3	12
0.2–0.002 (silt)		2	8
< 0.002 (clay)		1	4

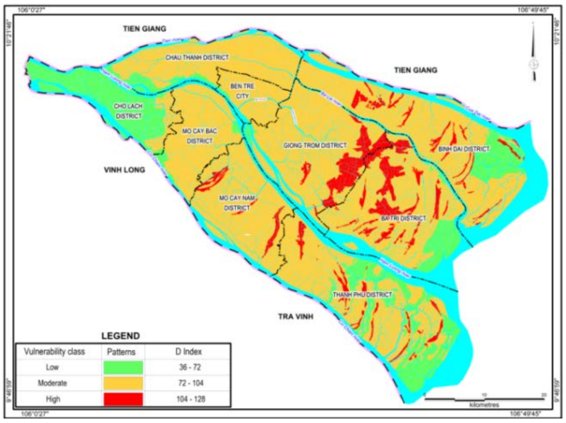

Figure 4. DRASTIC map of soil-water vulnerability to salinization

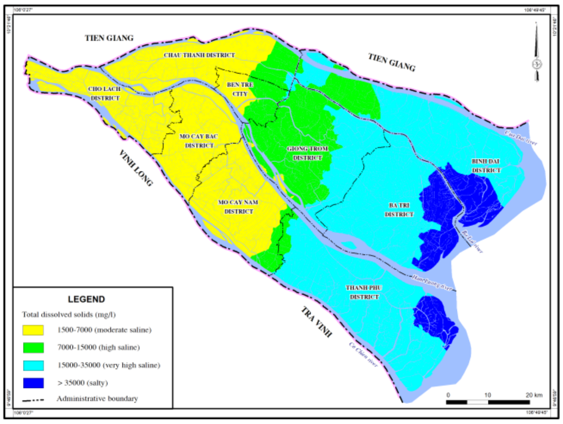

Figure 5. Map of TDS distribution at depth of 10–100 cm in Ben Tre province in 2018 [14]

CONCLUSION

The study used the DRASTIC model to assess soil-water vulnerability to salinization in Ben Tre Province. Based on the field investigation and laboratory experiment, seven factors were determined in the DRASTIC model: depth to soil water, recharge, soil-water bearing layer, soil media, topography, the impact of the root zone, and hydraulic conductivity. The resultant vulnerability map shows the predominant moderate vulnerability class in most of the Ben Tre Province, occupying an area of 79.28%. The low and high soil-water vulnerability classes occupy 14.55% and 6.17% of total natural area of the study area. Moreover, the soil-water vulnerability map was validated by TDS. The study results could be the scientific and practical basis for soil-water risk management to salinization for the study area.

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