Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Potential Effect of Mangrove Ecosystem on Soil Carbon Sequestration and its Physico-Chemical Properties

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Funding information:
Funding Agency: Slovak Research and Development Agency Grant Number: PVV-20-0281

Acknowledgement:
This work was supported by the Slovak Research and Development Agency under contract no. APVV-20-0281.

How to cite this article:
Abu-Hashim, M., Mousa, K.F., Merwad, A.E., Junakova, N., Bujansky, P., Zelenakova, M. and Abdellatif, A.A. (2024). Potential Effect of Mangrove Ecosystem on Soil Carbon Sequestration and its Physico-Chemical Properties. *Acta Monstanistica Slovaca,* Volume 29 (2), 276-285

DOI:
https://doi.org/10.46544/AMS.v29i2.04

Abstract

The mangrove ecosystem is a natural wetland located in the Red Sea that extends 500 km on the Egyptian western coast. It has great potential to sequestrate soil organic carbon, reduce atmospheric CO_2, and enhance soil hydro-physical properties. In this context, this research aims to characterise soil changes induced by mangrove growing. Both modelling and measurements herein were performed on five sampling areas at the Western Strand of the Red Sea (plus one control site - beach without plants). The locations (sites 1 and 2) of mangrove forest were in El-Gouna village with ages of 10 and 5 years, respectively, while (sites 3, 4, and 5) represent mangroves at Hurghada, Abu-Monquar Island, and Safaga, respectively. The mean values of measured soil organic carbon pool (SOCP) at the soil surface (0-90cm) revealed that the lowest values of the SOCP were at Hurghada with 8.81± 0.12 Mgha^{-1} and the highest values at Abu Monquar island with 59.75 ± 0.15 Mgha^{-1}. At El Gouna 1, 2 and Safaga, the SOCP values were 14.48, 12.86, and 39.98 Mgha^{-1}, respectively. In addition, the SOCP at the control site (beach without plants) was 6.62± 0.25 Mgha^{-1}. Thus, the mangrove ecosystem has a great potential to sequestrate the soil's organic carbon and reduce atmospheric CO_2. Soil bulk density (SBD) values varied at El-Gouna1, 2, and Hurghada from 1.63 to 1.75 g/cm³, while the lowest SBD values were observed at Abu-Monquar Island and Safaga with 1.31± 0.02, g/cm³ and 1.53 ± 0.05 g/cm³, respectively. SBD at the control site was 1.75± 0.05 g/cm³, which reflects the higher values. Morphological characteristics reveal that tree height results varied from 110-130 cm, 50-70 cm, 150-200 cm, 200-300 cm, and 200-270 cm for ElGouna1, ElGouna2, Hurghada, Abu-Manqar, and Safaga, respectively. Higher values of tree height, size index, and density are convenient, as are the lower values of SBD at Abu-Monquar and Safaga compared to other site locations. The soil-water HYDRUS-1D model revealed that the soil water storage capacity at Abu-Monquar was higher than the other samples. Thus, the joint use of modelling and measurements enabled deeper insight and a suitable characterisation of soil physicochemical changes induced by mangrove growth.

Keywords

Mangrove ecosystem; Physical properties; Red Sea; Morphological, HYDRUS-1D code.

Introduction

Mangrove ecosystems contribute to 0.7% of the global coastal zone, which can sequestrate 25% of soil carbon. It has been estimated that mangrove ecosystems can sequester around 25% of soil organic carbon at the soil surface (Alongi, 2007). In Egypt, two main mangrove species grow; the first type is Avicennia marina, which is distributed along the Red Sea coast, while the second is Rhizophora mucronata, which grows and is distributed mainly in the southern part of the Red Sea coast beginning from the city of Shalatein of Latitude 23° 28′ N, and southward to the city of Mersa Halaib with Latitude 22° 10′ N (Abdellatif et al., 2022). The Avicennia marina, along the northern coast of the Red Sea, has a great potential to sequestrate in Egypt, where the mean carbon sequestration was identified as 85 Mg C ha^{-i}. Nevertheless, the mean potential of carbon sequestration was estimated as 0.061 Mg C ha^{-1} year (Kathiresan and Bingham, 2001).

Owing to the ecological importance of mangrove forests, there is a need for deeper insight and monitoring to enhance their knowledge and also contribute to identifying conservation strategies that are even more extremely important under changing climatic scenarios. In addition, Mashaly et al. (2016).investigated the effect of mangrove vegetation at the Gulf of Aqaba–Egypt, on the stored soil carbon, and they estimated as 41.9, 70.3, 109.3 Mg C $ha^{-[}$ at the shoreline, salt plain habitats and intertidal, respectively. The mangrove has the capability to carbon sequestration potential besides the other coastal plant ecosystems on the Gulf of Aqaba, where carbon sequestration by mangrove reached 2.4, 1.04, 0.545, 0.81 and 0.14 Mg C ha^{-2} $year^{-y}$ of intertidal, salt plains, shoreline, hypersaline ecosystems and mudflats, respectively (Eid and Shaltout, 2016; El Hussieny (2021), that had effects on the different soil hydro-physical parameters. McSherry et al. (2023) highlighted that mangal locations' geomorphological and biophysical qualities are important parameters for maximising mangrove forest carbon sequestration. Undoubted-ly, mangroves have a high efficiency in sequestering soil carbon with a rate of approximately 85 Mg C ha^{-1}, which is particularly significant in Egypt, where the estimated mean of the soil carbon sequestration is approximately 0.061 Mg C ha^{-1} $year^{-1}$ (Mashaly et al., 2016; Eid and Shaltout, 2016).

Nevertheless, compared to the assessments of the mangrove's potentiality for carbon sequestration, there is a gap in knowledge on its impact on the soil's hydraulic properties. The objective of this paper is to contribute to filling this gap.

Problem definition

The rate of soil water infiltration and the consequence of the water movement in its matrix are an important consideration in developing the agro-ecosystems and the land-management practices that aim to preserve a relevant soil water environment crucial for a favourable plant and soil health (Abu-Hashim, 2022). In comparison, the hydraulic properties of soil have received little attention, maybe due to the difficulties in providing accurate soil physical measurements. Laboratory and field methods for investigating soil hydraulic properties are costly and/or time-consuming (Van Genuchten, 1980). Laboratory methods that depend on the direct solution of Darcy's law (Bouma et al., 1982; Corey, 2018) for the determination of hydraulic properties, such as the transient procedures involved and based on Richards' equation of approximation, are still used as an efficient tool for identifying the soil hydraulic properties. Ramos (2006) found that realistic results depend on field measurements rather than laboratory measurements because they retain soil continuity versus depth.

Infiltration parameters have long been an essential characteristic of soil and water research due to their important role in the concept of land management (Abu-Hashim et al., 2022). Several mathematical models have been developed over the last decades to compute infiltration rates. These infiltration-based models are generally classified into empirical, semi-empirical, and physically based models (Abu-Hashim, 2011; Said et al., 2020). The empirical and/or semi-empirical models, as the models of Kostiakov and Horton, are performed in simple equations form and prepared from field, pedotransfer, and/or laboratory experimental data (Mishra et al., 2003). Nevertheless, neither the empirical nor semi-empirical models can provide detailed, clear results on infiltration and their impacts on the soil's physical properties (Brunone et al., 2003). These physical-based models depend on the Richards equation as one of the most efficient tools for identifying water flow, and these equations are primarily built upon Darcy's law and the principle of mass conservation (Lei et al., 1988). By employing such models, researchers can better understand the intricate mechanisms involved in water infiltration, allowing for more accurate simulations and predictions. The current research aimed to identify and analyse *in-situ* the soil hydro-physical changes in the carbon sequestration induced by mangrove and their impacts on preserving the soil quality. Thus, we implemented the Hydrus-1D based on the obtained real field data to simulate and analyse two key conditions:

(1) soil water dynamics under Mangrove planting,
(2) soil hydro-physical relations in terms of the influence of mangroves on hydraulic conductivity.

Material and methods

Description of the study area

The Red Sea geographically extends from the Bab El Mandab strait at 12° 39′ in the south to Ras Mohammed in the north at 27° 43' and is divided into two main gulfs: Suez Gulf to the west and the Aqaba Gulf to the east

(Google Earth Pro, 2017). The Red Sea coast is allocated with 870 Km inside the Egyptian territory. Thus, Saifullah (1996) mentioned that the combined length of the Red Sea coastline in Egypt, including both the Aqaba Gulf and Suez Gulf, is approximately 1700 km. The present study primarily concentrates on the mangroves situated and growing along the Egyptian coast (Fig. 1), encompassing various islands into the Red Sea Abu Monquar Island to the Hurghada city (27.216250° N, 33.876288° E).

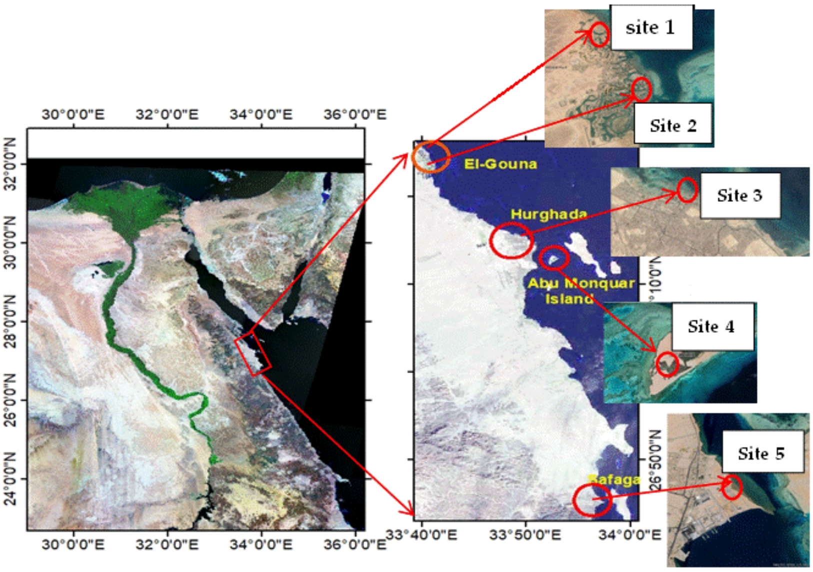

Fig. 1. Sample locations of the mangrove sites along the Egyptian Red Sea coast

The mangrove sample locations were identified within the designated study area that spans from the Island of Abu Monquar (27.216250° N, 33.876288° E) and extends northwards towards Hurghada city. A total of five sampling sites were included in this study (plus one control site – a beach without plants). The primary objective of the research was to identify and represent the effects of the mangrove pure population of Avicenna Marina type on the soil's hydro-physical properties. The mangrove sites at (Site 1 and Site 2) located in El-Gouna village, represented mangrove plantations aged 10 and 5 years, respectively. Meanwhile, mangrove sites 3, 4, and 5 corresponded to mangrove locations in Hurghada, Abu Monquar Island, and Safaga, respectively. The selected areas exhibit specific climatic conditions, characterised by annual temperature with an average of 25 °C and an average annual solar radiation of 28.9 Mj m^{-2}, while the annual mean rainfall presented with 5.9 mm year^{-1} (Weather-base.com, 2021).

In-situ measurements and soil laboratory analysis

The soil profile at each chosen site underwent a comprehensive examination, extending to a depth of 90 cm. Extensive soil samples were collected along three transects, encompassing five distinct locations within each transect. To ensure representative sampling, soil samples were specifically obtained from three different soil layers: 0-30 cm, 30-60 cm, and 60-90 cm. The selected soil samples were subsequently air-dried and subjected to a range of physical and chemical analyses, facilitating a comprehensive evaluation of their properties. In-situ measurements were conducted at field locations to determine the dry bulk density at each soil layer. So, using hammering sample rings with a fixed volume of 100 cm³ into a soil matrix, the soil samples were collected for the dry bulk density.

The soil samples in the laboratory were air-dried at room temperature, and the soil ground to pass through a 2-mm sieve. The pH of the soil was measured using a lab pH meter - model PH211 by extracting the soil with a 1:2.5 ratio of soil to water. Electrical conductivity (EC) was assessed using a conductivity meter to determine the salinity of the soil paste extract. The soil's total calcium carbonate content was examined using Sparks' method (Sparks et al., 2020). The international pipette method (Klute, 1986) was used to analyse the soil particle-size distributions. The soil saturation percentage, field capacity, and wilting points were performed according to (Klute, 1986). The morphological characteristics of the mangrove forests (Tab. 2), including tree height, tree size index, trunk circumference, and tree density for each location, were identified to investigate the population growth influences of the mangrove forest on the soil physical properties (Teraminami et al., 2014).

Physicochemical Parameters of Soil Samples and Soil Organic Carbon Pool Calculation

Soil coarse fraction content (particles >2 mm in diameter) was determined according to Lal *et al.* (1999) and Post and Kwon (2000):

gravel content (%) = (weight of coarse materials/ weight of coarse and fine materials) × 100 (1)

Calculation of the SOCP was carried out as a parameter of SOC concentration (Lal *et al.*, 1999). The soil organic matter (SOM) content for each horizon was first converted to SOC percentage by multiplying the SOM by a factor of 0.58 (Lal *et al.*, 1999; Abu-Hashim *et al.*, 2016). For each soil horizon, SOCP (kg C m^{-2}) was calculated by multiplying the SOC percentage by the soil depth (30 cm), soil bulk density (Mg m^{-3}), and soil fraction (<2 mm in size) (Lal, 2003):

$$SOCP = [L \times B.D \times SOC \times (1- F/100)] /10 \qquad (2)$$

Where *SOCP* is the soil organic carbon pool for each soil horizon (kg m^{-2}), L is the thickness of the soil layer (30 cm), *SOC* is soil organic carbon content (wt %), *F* > 2 mm coarse soil fragment (wt %), and *B.D* is the soil dry bulk density (Mg m^{-3}). Based on the soil organic carbon sequestrated on the soil surface, emitted carbon dioxide (CO_2) was calculated using the following equation of IPCC (2007):

$$\text{Emitted } CO_2 = \text{Amount of Sequestrated Soil Organic Carbon } X\ 3.67 \qquad (3)$$

The factor 3.67 equals the molecular weight of CO_2 divided by the atomic weight of carbon. IPCC did not use 44 and 12, respectively, but the weighted average of molecules containing the several carbon isotopes found in the atmosphere, mainly 12C and 13C.

Simulation of one-dimensional water flow

To investigate the soil water dynamics under mangrove forests, the HYDRUS-1D model was utilised in this work, which was numerically performed by Simunek et al. (2005). The HYDRUS-1D model depended on the Richards equation used to simulate the water flows in one-dimensional media with varying saturation levels (Fig. 2).

Fig. 2. The morphological appearance of the different sample locations, Site1: Gouna1, Site2: Gouna2, Site3: Hurghada, Site4: Abu-Manqar, Site5: Safaga.

The Richard flow equation was explained as follows:

$$\frac{\partial\theta(h,t)}{\partial t} = \frac{\partial}{\partial z}\left[k(h)\left(\frac{\partial h}{\partial z}+1\right)\right] \qquad (4)$$

where: θ is volumetric water content; t is time; h is soil water pressure head; z is vertical coordinate at the soil surface (negative downward); and $k(h)$ is unsaturated hydraulic conductivity. The initial boundary condition and the upper boundary condition were:

$$h(0,t)=h0$$
$$h(z,0)=hi(z)$$

$h0$ is the water potential at the upper soil surface, while $hi\ (z)$ is the initial water pressure head. Through the processes into the HYDRUS-1D model, we applied the Van Genuchten-Mualem model for the investigated locations (2):

$$\frac{\theta-\theta r}{\theta s-\theta r}=(1|\alpha h|n)\text{-}m \qquad h>0 \qquad (5)$$

$$\boldsymbol{\theta=\theta s} \qquad h\leq 0$$

where: θ is volumetric soil water content ($cm^3.cm^{-3}$), θs and θr are the saturated and residual water contents ($cm^3.cm^{-3}$), and h is the soil water pressure head (cm). The constants of the Van Genuchten-Mualem model, m, n, and α, are the empirical parameters, and the m value is calculated using the Van Genuchten-Mualem model with $m=1-1/n$. As the HYDRUS-1D code connected with hierarchical computations (ROSETTA model) of Koepf et al. (1976), the ROSETTA model used to compute the pedo-transfer functions (P.T.F.s), which are used to predict the soil water retention characteristics and the saturated hydraulic conductivity (Ks) of van Genuchten parameters in a hierarchical manner using in sit measured soil textural distribution, soil bulk density, water content at field capacity and water content at wilting point as inputs (Schaap et al., 2001). We performed the van Genuchten-Mualem model with no-hysteresis for the initial and boundary conditions to identify the soil hydraulic properties for all the locations. In addition, we implemented the location's upper boundary conditions with a pressure head of -5 cm, while the location's lower boundary condition presented as free drainage.

Results and Discussions

Soil physical properties under the Mangrove ecosystem

The soil bulk density (SBD) values obtained from the different locations indicated that the soil dry bulk density was higher in the upper soil layers (0-30 cm) than in the lower soil layers. At the control site, the soil dry bulk density values were 1.75 g/cm³, 1.70 g/cm³, and 1.70 g/cm³ at soil depths of 0-30 cm, 30-60 cm, and 60-90 cm, respectively (Tab. 1). The cultivated locations with the mangrove plants revealed another SBD values in their different layers, where the site S1 in El Gouna location, man-grove had been planted for ten years, the SBD values presented 1.63 g/cm³, 1.60 g/cm³, and 1.50 g/cm³ at soil layers of 0-30 cm, 30-60 cm, and 60-90 cm, respectively. Similarly, for the second site in El Gouna village with the same species of mangrove planted for five years, the SBD values were 1.70 g/cm³, 1.64 g/cm³, and 1.58 g/cm³ at soil layers of 0-30 cm, 30-60 cm, and 60-90 cm, respectively. For Hurghada location (S3), the soil dry bulk density was 1.73 g/cm³, 1.64 g/cm³, and 1.60 g/cm³ at soil layers of 0-30 cm, 30-60 cm, and 60-90 cm, respectively. For the Island of Abu Monquar (S4), the SBD values represented 1.31 g/cm³ and 1.20 g/cm³ at soil layers of 0-30 cm and 30-60 cm, respectively. In the Safaga location (S5), the soil dry bulk density value records 1.53 g/cm³ at a soil layer of 0-30 cm (Tab. 1).

Soil Organic sequestration with Land Use

The physical properties of soil in the catchment area indicated that the dominant soil types are sandy and sandy loam soil (Table 1). Soil field capacity varied from 9.6% to 16.8%, while dry bulk density varied from 1.2 to 1.75 Mg m^{-3}.

Computing soil organic carbon pool (SOCP) using equation 2 under different land uses for the whole catchment and performing the land-use area in hectares, SOCP of 1 [t $\cdot ha^{-1}$] is equal to 10 [kg m^{-2}]. The mean values of measured soil organic carbon pool (SOCP) at the soil surface (0-90cm) revealed that the lowest values of the SOCP were at Hurghada with 8.81± 0.12 t ha^{-1} and the highest values at Abu Monquar island with 59.75 ± 0.15 $Mgha^{-1}$ (Figure 3). While at El Gouna 1, 2 and at Safaga, the SOCP values were 14.48, 12.86, and 39.98 t ha^{-1}, respectively (Fig. 3), and these results are relevant to the obtained DBD results in Fig. 2 (Datta et al., 2015; Jobbagy and Jackson.,2000). In addition, the soil organic carbon pool at the control site (beach without plants) was 6.62± 0.25 $Mgha^{-1}$. SOCP degradation could encourage CO_2 emission. These results are convenient with the findings of El-Hussieny et al. (2021) in the Red Sea region. Therefore, using equation 3, the emitted CO_2 to the surrounding atmosphere resulting from losing the cropland amounts to 1047.5 Gg $CO_{2,}$ which is relevant to the finding of El-Hussieny and Ismail (2017) at South Sinai.

Tab. 1. The investigated soil physicochemical properties under the Mangrove planting

Site	**Ec (soil paste) mmhos/cm**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Soil Texture**	**Bulk Density**	**W.P. (%)**	**F.C. (%)**	*SOC (%)*	*SOCP Mgha^{-1}*
Cont (A)	8.447	92.33	5.40	2.27	Sand	1.75	4.77	9.54	*0.123*	*5.17*
Cont (B)	9.792	93.00	4.87	2.13	Sand	1.70	4.65	9.29	*0.180*	*7.34*
Cont (C)	10.458	93.00	4.65	2.35	Sand	1.70	4.71	9.42	*0.180*	*7.34*
S1 A	17.887	91.00	5.63	3.37	Sand	1.63	6.07	12.14	*0.324*	*12.67*
S1 B	21.250	92.33	4.60	3.07	Sand	1.60	6.11	12.22	*0.314*	*12.06*
S1 C	18.167	92.00	4.60	3.40	Sand	1.50	5.65	11.30	*0.520*	*18.72*
S2 A	13.783	91.33	4.97	3.70	Sand	1.70	6.11	12.22	*0.229*	*9.34*
S2 B	15.783	91.33	5.04	3.63	Sand	1.64	6.15	12.31	*0.296*	*11.65*
S2 C	17.467	90.33	5.19	4.48	Sand	1.58	5.69	11.39	*0.464*	*17.59*
S3 A	16.400	91.50	4.77	3.73	Sand	1.73	5.84	11.68	*0.200*	*8.30*
S3 B	16.163	91.50	5.25	3.25	Sand	1.64	5.90	11.81	*0.213*	*8.38*
S3 C	17.213	91.00	5.25	3.75	Sand	1.60	6.03	12.06	*0.254*	*9.75*
S4 A	88.138	78.50	12.50	9.00	Sandy loam	1.31	8.01	16.01	*1.847*	*58.07*
S4 B	26.600	89.00	5.50	5.50	Sand	1.20	8.41	16.83	*2.133*	*61.42*
S5 A	17.680	90.60	5.15	4.25	Sand	1.53	7.74	15.47	*1.091*	*39.98*

Cont: control, S1: Gouna1, S2:Gouna2, S3: Hurghada, S4: Abu-Manqar, S5: Safaga, A: Soil depth 0-30cm, B: Soil depth 30-60cm, C: Soil depth 60-90cm.

The findings presented in Tab. 1 indicate notable variations in calcium carbonate ($CaCO_3$) values among the different sites. The highest $CaCO_3$ content was exhibited at Abu Monquar Island, with 16.82%. In contrast, El-Gouna1, El-Gouna2, Hurghada, Safaga, and the control sites had $CaCO_3$ contents of 2.66%, 6.93%, 5.85%, 9.19%, and 2.69%, respectively, for the soil surface (0-30 cm).

The obtained soil physical properties for the investigated locations revealed significant differences, particularly at the Island of Abu Monquar, which showed increased values in field capacity compared to the other locations, mainly in the upper soil layer. At Abu Monquar Island, the field capacity was 16%, while the other sites exhibited values of 9.54%, 12.14%, 12.22%, 11.68%, and 15.47% for the control and Sites 1, 2, 3, and 5, respectively. These findings are consistent with the results reported in (Abdellatif et al., 2022; Oquist et al., 2006).

The results of Tab. 2 revealed the morphological characteristics of the mangrove forests, including the tree height, tree size index, trunk circumference, and tree density for each location. That the tree height results varied from 110-130 cm, 50-70 cm, 150-200 cm, 200-300 cm, and 200-270 cm for El-Gouna1, El-Gouna2, Hurghada, Abu Monquar, and Safaga, respectively. The trunk circumferences were 20 -30 cm, 10-20 cm, 22-35 cm, 25-45 cm, and 25-40 cm for ElGouna1, ElGouna2, Hurghada, Abu Monquar, and Safaga.

Tab. 2. The morphological characteristics of the mangrove forests for each location

Site	Tree height (cm)	Tree size index (cm)	Trunk circumference (cm)	Tree density (individual per 100 m^2)
S1	110 -130	90 - 110	20 - 30	3.4 – 15.5
S2	50 - 70	30 - 40	10 - 20	2.5 – 10.5
S3	150 - 200	130 - 170	22 - 35	4.2 – 20.2
S4	200 - 300	150 - 220	25 - 45	5.5 – 27.5
S5	200 - 270	155 - 210	25 - 40	5.1 – 25.5

S1: Gouna1, S2:Gouna2, S3: Hurghada, S4: Abu-Manqar, S5: Safaga.

The results of the morphological characteristics of the mangrove forests for each location were appropriated with the findings of the soil physic-chemical properties (Tab. 1). The higher values of the trunk circumference, tree height, tree size index, and tree density convenient with the lower values of the SBD at the Island of Abu Monquar and Safaga with compared to the other site locations.

Simulation of the soil water flow using a one-dimensional model

The soil hydrological parameters of the investigated sites under mangrove planting are shown in Tab. 3. With implementing the obtained results of the measured particle size distribution, dry bulk density, and in-situ saturated hydraulic conductivity in the van Genuchten-Mualem model into the Hydrus-1D model, the hydrological parameters (Qr, Qs, α, n) were obtained (Tab. 3). The obtained results were consistence with the obtained results by (Abu-Hashim, 2011; Jacques et al., 2002) for field experiments that imposed a water pressure head through a disc infiltrometer for the infiltration tests to estimate the hydraulic parameters.

Tab. 3. Hydraulic properties of the investigated soils under Mangrove growing

Sites	Theta r (cm^3/cm^3)	Theta s (cm^3/cm^3)	Alpha (1/cm)	n	Ks (cm/day)
C1 (A)	0.046	0.3152	0.0341	2.2038	130.27
C2 (B)	0.0474	0.3292	0.0325	2.313	156.94
C3 (C)	0.0478	0.3295	0.0328	2.3352	164.36
S1A	0.049	0.3501	0.0327	2.2498	171.02
S1B	0.0506	0.3594	0.0327	2.4524	236.63
S1C	0.0519	0.3907	0.033	2.4559	313.32
S2A	0.0467	0.3325	0.0304	1.9766	91.76
S2B	0.048	0.3497	0.0296	2.0469	115.31
S3C	0.051	0.3672	0.0325	2.2231	191.09
S3A	0.0466	0.3239	0.0317	2.0013	94.26
S3B	0.0478	0.3487	0.0301	2.0976	125.16
S3C	0.0491	0.3611	0.0304	2.1191	145.96
S4A	0.0505	0.4424	0.039	1.6818	231.1
S4B	0.0495	0.4794	0.0387	1.6996	449.5
S5A	0.0482	0.3845	0.0259	1.8463	107.73

Theta r (Qr): Residual water content (cm^3 cm^{-3}); Theta s (Qs): Saturated water content (cm^3 cm^{-3}); Alpha: Sorptivity number (1/cm); n: pore-size distribution index. Ks: Saturated hydraulic conductivity (cm d^{-1}). C: control, S1: Gouna, S2:Gouna2, S3: Hurghada, S4: AbuManqar, S5: Safaga. A: Soil depth 0-30cm, B: Soil depth 30-60cm, C: Soil depth 60-90cm

Fig. 3 shows the relation between the volumetric water content (theta potential), which was solved by the method of (Simunek et al., 2005; Koepf et al., 1976) with the time under mangrove planting of the different investigated sites at two soil depths 10 and 20 cm. The results revealed that the volumetric water content (theta potential) of site 4 (Abu Monquar Island) was higher than the other investigated sites at the same soil depths. This may be attributed to the difference in soil texture and the increase of clay content (Tab. 1), which have affected the soil water movement and consequently increased the volumetric water content compared with other sites, as shown in Fig. 3.

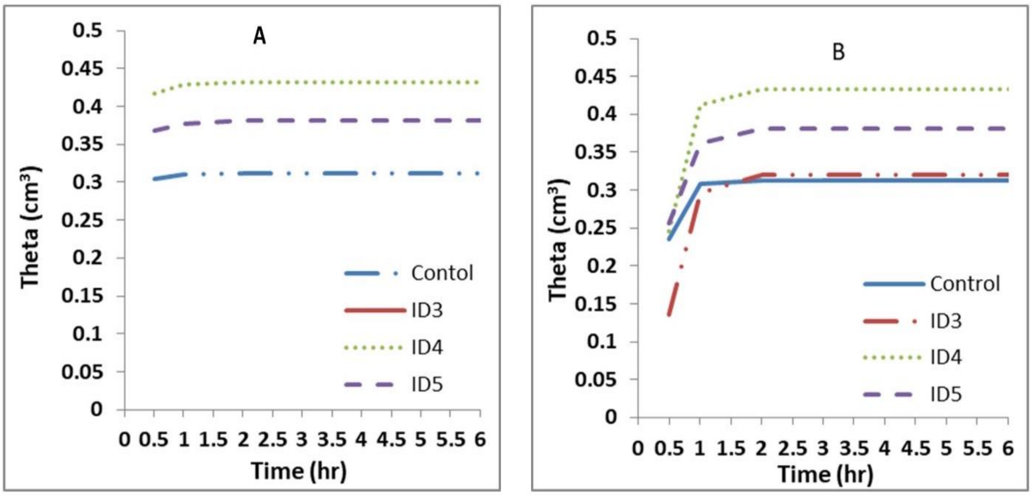

Fig. 3. Changes of volumetric water content with time under two different depths (A) at soil depth 10cm and (B) at soil depth 20cm using mangrove growing at the different sites using the numerical model Hydrus-1D. ID3: Hurghada, ID4: Abu Monquar Island, ID5: Safaga

The results of Fig. 4 revealed the impact of the Mangrove stands on soil water flow using the numerical model Hydrus-1D. The cumulative infiltration curve under Site 4 was more abundant than the other sites (Fig. 4d). The results of Fig. 4a showed the effects of water retention during the infiltration process. The results of Fig. 4b presented the Ks versus the volumetric water content, which reflected the same trend of increasing Ks under Site 4 compared with the other investigated sites with increasing the water in soils, which is relevant to the concepts (Abu-Hashim, 2011; Zhao et al., 2023).

The soil water storage capacity at Abu Monquar Island (Site 4) was higher than the other sample locations. In addition, the soil cumulative infiltration rate at Abu Monquar Island was higher than the other sample locations. The soil physical changes induced by Mangrove growing practices at Abu Monquar Island reflect better soil quality which will encourage planting the Mangrove in large spaces compared to the other sites, that is could be interpreted due to increasing the clay content (Abu-Hashim et al., 2021; Poudel et al., 2001), higher biological activity, more calcium carbonate in the soil (El Hussieny et al., 2021 Zhao et al., 2023), and so higher infiltration capacity (Abu-Hashim et al., 2022; Ibrahim et al., 2023). These results are relevant to the findings of Abu-Hashim (2011).

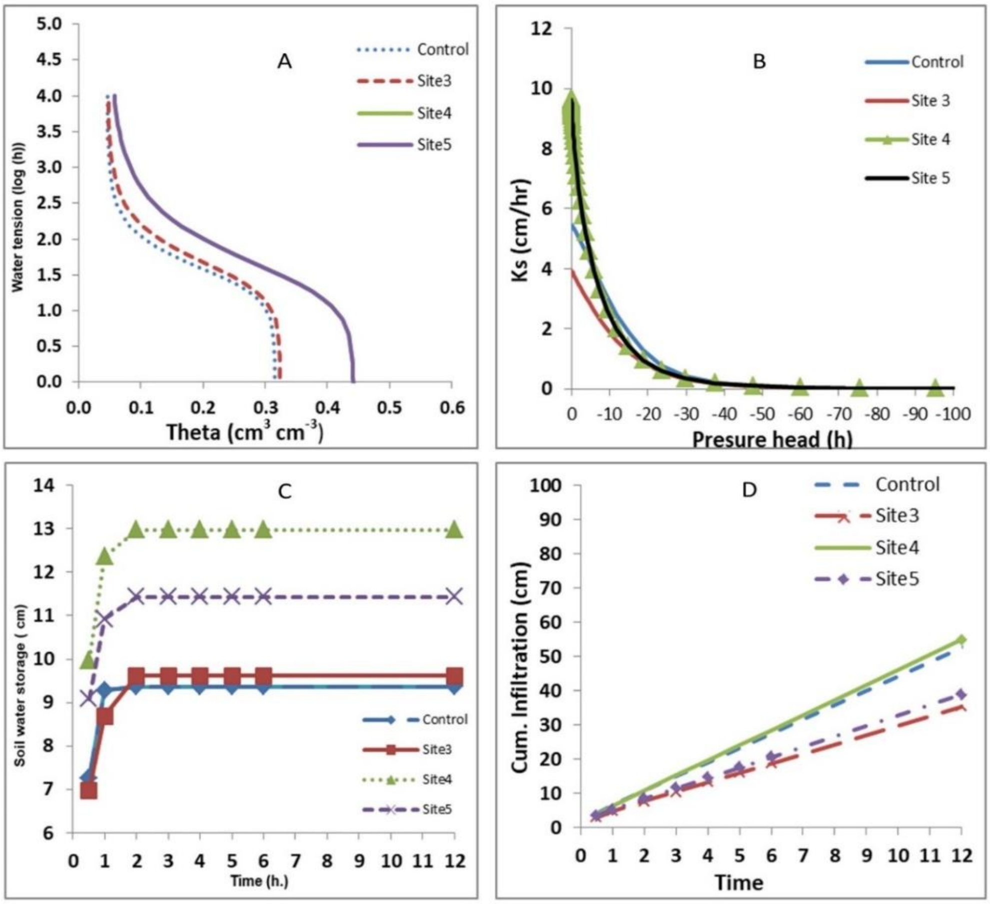

Fig. 4. Hydraulic Properties under Mangrove stands at the different sites A: Water retention curves, B: saturated hydraulic conductivity versus pressure head, C: Soil water storage capacity versus time, D: Cumulative infiltration versus time.

Conclusions

The present study indicators at the Red Sea coast showed the mangroves that are distributed and grow as discontinuous patches. Mangrove swamps (Avicennia marina) have several difficulties that affect the water movement into the soil, leaves, prop roots, and pneumatophores, which could affect the sedimentation of the suspended particles in the surrounding areas, affecting soil carbon sequestration. The soil clay content reveals the main factor that affects the different hydro-physical under the different sites. The minimum dry bulk density values were noticed at Abu Monquar Island, which has the highest clay content compared to the other investigated sites. The soil clay content reveals the main factor that affects the different hydro-physical under the different sites. The minimum dry bulk density values were noticed at Abu Monquar Island, which has the highest clay content compared to the other investigated sites.

In addition, the Calcium carbonate values were highest under Abu Monquar Island compared to the other sites. The HYDRUS-1D model results provided a reliable simulation of the cumulative infiltration and infiltration rate into the soil. Using the model HYDRUS-1D to investigate the soil hydro-physical properties proved an efficient tool for the mangrove ecosystem assessment of the soil's physical properties.

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