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A numerical approach to accurately estimate water resistivity (R_w) and saturation (S_w) in shaly sand formations

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Abstract: In hydrocarbon reservoirs, the accuracy of hydrocarbon saturation depends on the precision of the water saturation and resistivity (S_w and R_w). A significant interpretation parameter is the resistivity of formation water (interstitial water or connate water which is, uncontaminated by the drilling mud that saturates the porous formation rock) because it is appropriate for the calculations of saturation (water and/or hydrocarbon) from basic resistivity logs. The most reliable way to determine this value is through the determination of the chemical composition or resistivity of uncontaminated connate water inside the formation. The saturation of water is the ratio between water volume to total pores volume and its determination accuracy has a great role in estimating hydrocarbon volume. However, the aims of this paper have two main folds, firstly, to introduce a complete review on water resistivity, saturation, and shale volume. Secondly, it presents a numerical method for the determination of resistivity of connate water and water saturation from the true resistivity of the formation using *Schlumberger (1975)* in shaly sand formations which require critical treatment compared to the clean sand reservoirs. To ensure its ability to determine both the resistivity and saturation of formation water, the technique was tested using synthetic and real field data.

Key words: shaly-sand reservoirs, water resistivity, water saturation

1. Introduction

Because there are many shaly sand reservoirs and some of them are rich with hydrocarbon, a wide assortment of procedures are used for shaly sand reservoirs as the estimation of water resistivity which is considered a necessary parameter to calculate water saturation then hydrocarbon in place. In all cases, the accurate value of water saturation can be easily achieved through water sample measurements. However, as for water saturation in the shaly reservoir, there is no one method hegemony within the industry.

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Mabrouk et al. (2013) introduced a simple numerical approach to calculate the resistivity of connate water with a very high level of precision and with a neglected amount of error which depends on the Archie water saturation equation, which is only valid for clean reservoirs. In this paper, we introduce a similar numerical technique to estimate both connate water resistivity (R_w) and water saturation (S_w) in shaly sand formations.

In 1942, Archie introduced the water saturation equation in clean formation and it has been widely used.

$$S_w^n = \frac{F\,R_w}{R_t}\,, \tag{1}$$

where F = formation factor (a/ϕ^m), ϕ = porosity, S_w = water saturation fraction, R_w = water resistivity Ω.m, R_t = true formation resistivity Ω.m, a = tortuosity factor, n = saturation exponent (also usually near 2), m = cementation exponent.

But Archie equation can not be used in shaly sand and heterogeneous formation due to the presence of clay that adds an additional conductivity. Log analysis solutions for water saturations in Shaly sand reservoirs are elaborations of Archie equation, with extra terms that accommodate volumes of shale or bound water and their associated electrical properties.

There are a large number of alternative shaly sandstone equations. These are used today, because no unquiely satisfactory solution has been reached. With the typical situations of limited subsurface information and the variety of shaly sandstones. However, if models are used from a utility point of view, the calibration inside a shaly sandstone reservoir can be performed based on a provisional recognition of water zones as an optimization problem.

Our main motivation is to accurately determine R_w & S_w using machine learning via the introduced "Software application" in shaly sand formations, the method can be also extended in complex lithology.

1.1. Review on water resistivity (R_w) measurement techniques

One of the most important parameters for the hydrocarbon saturation measurement in reservoirs is R_w, which can be calculated by graphical (*Hingle, 1959; Pickett, 1972*) or analytical (*Archie, 1942; Dresser Atlas, 1975; Bateman and Konen, 1977; Hassan et al., 2014*) methods:

1. laboratory measurement for an extracted water sample directly (most accurate method),
2. chemical analysis method,
3. from self-potential (*Asquith and Gibson, 1982*),
4. R_{wa} technique (*Schlumberger, 1972*),
5. the use of the ratio method,
6. form cross plots (*Hingle, 1959; Pickett, 1972*),
7. catalogs of water resistivity.

1.2. Water saturation (S_w) calculations review

Water saturation (S_w) is one of the most important parameters to calculate the hydrocarbon saturation (S_h) and consequently the oil in place (OIP) (*Hassan et al., 2014; Abuzaied et al., 2020*). The following tables (Table 1a,b) depict the different techniques and formulas used in calculating such important parameters in both clean and shaly formation.

1.2.1. In clean formations

Table 1a. Water saturation calculations review (clean formations).

Method	Equation used
Archie (1942)	$S_w^n = \dfrac{F\,R_w}{R_t}$ (1)
R_{wa} method If the formation is assumed to be fully saturated with water, the Archie equation is then reduced to $R_{wa} = R_t/F\,,$ R_{wa} is the apparent water resistivity if the formation is 100% saturated with water.	$S_w = \sqrt{\dfrac{R_w}{R_{wa}}}$ (2)
Resistivity ratio method In this process, it is presumed that the model is divided into	$\left(\dfrac{S_w}{S_{xo}}\right)^2 = \dfrac{R_{xo}/R_t}{R_{mf}/R_w}$ (3)

two different regions, invaded and uninvaded. The limitation emerges from the failure of any resistivity system to obtain either R_{xo} or R_t, completely independent of the other device.	R_{mf} is the mud filtrate resistivity in the invaded zone; R_w is the resistivity of water in the uninvaded zone; R_{xo} is the formation resistivity in the invaded zone; R_t is the true formation resistivity (uninvaded zone).
Schlumberger (1977)	$$(S_w)_{COR} = S_{wa} \times \left(\frac{S_{wa}}{S_{wr}}\right)^{0.25} \quad (4)$$ $(S_w)_{COR}$ is the corrected saturation of water in the uninvaded zone. S_{wa} is the saturation of water in the uninvaded zone using the method of Archie. S_{wr} is the uninvaded zone, a saturation of water (ratio method).

1.2.2. In shaly formations

Table 1b. Water saturation calculations review (shaly formations).

Method	Equation used
Archie (1942)	$$S_w = \sqrt{F\,R_w \times \left(\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}\right)} \quad (5)$$ S_w is the saturation of water in the uninvaded zone. R_w is the water resistivity. F is the formation resistivity factor. R_{sh} is the shale resistivity. V_{sh} is the shale volume.
De Witte (1950)	$$S_w = \frac{R_w}{2\phi}\left[-y + \sqrt{y^2 - \left(\frac{4}{R_w}\right)\left(\frac{V_{sh}^2}{R_c} - \frac{1}{R_t}\right)}\right] \quad (6)$$ where $$y = V_{sh}\left[\frac{1}{R_w} + \frac{1}{R_c}\right] \quad (7)$$
Poupon et al. (1954) For saturation of water, which holds for both shaly and clean	$$S_w = \sqrt{\frac{a}{\phi^m}\left[\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}\right]\frac{R_w}{(1 - V_{sh})}} \quad (8)$$

sand, he proposed the following equation.	
Hossin (1960) He assumed a clay-sand model that allows water saturation in shaly sands to be measured if the resistivity of water formation, porosity, and shale volume is known. He derived a model that corresponds with the previous *De Witte (1950)* and *Poupon et al. (1954)* models, where shaliness varies from 10:30 percent and diverges at higher percentages.	$$\mathrm{S_w} = \sqrt{\frac{0.9}{\phi}\left[\frac{1}{\mathrm{R_t}} - \frac{\mathrm{V_{sh}^2}}{\mathrm{R_c}}\right]\mathrm{R_w}} \qquad (9)$$ $\mathrm{R_c}$ is the dispersed clay resistivity and can be approximated by: 0.4 $\mathrm{R_{sh}}$.
Simandoux (1963) This equation is used to obtain the saturation of water, assisted by laboratory experiments at the French Petroleum Institute.	$$\mathrm{S_w} = \left[\left(\frac{-\mathrm{V_{sh}}}{\mathrm{R_{sh}}}\right) + \sqrt{\left(\frac{-\mathrm{V_{sh}}}{\mathrm{R_{sh}}}\right) + \frac{5\phi^2}{\mathrm{R_t R_w}}}\right]\frac{0.4\,\mathrm{R_w}}{\phi^2} \qquad (10)$$
Waxman and Smits (1968) This model needs awareness of seven parameters fractional porosity (ϕ_{T}), the resistivity of formation ($\mathrm{R_t}$), resistivity of formation water ($\mathrm{R_w}$), exponent of shaly sand saturation (n), exponent of shaly sand cementation (m), equivalent clay counter ion conductivity (B), and capacity of exchange of cations per volume unit ($\mathrm{Q_v}$).	$$\mathrm{S_w} = \frac{\mathrm{F\,R_w}}{\mathrm{R_t}}\left(1 + \frac{\mathrm{R_w\,B\,Q_v}}{\mathrm{S_w}}\right) \qquad (11)$$

Bardon and Pied (1969) The Simandoux equation was also presented as shown in Eq. (12). By using R_{sh} (shale resistivity) and V_{sh} (shale volume). *Bardon and Pied (1969)* modified the Simandoux equation by including water saturation to the original Simandoux equation which turned Eq. (12) into Eq. (13).	$$\frac{1}{R_t} = \frac{S_w^2}{F\,R_w} + \frac{V_{sh}\,\epsilon}{R_{sh}} \qquad (12)$$ $$\frac{1}{R_t} = \frac{S_w^2}{F\,R_w} + \frac{V_{sh} * S_w}{R_{sh}} \qquad (13)$$
Fertl and Hammack (1971) Two different saturation exponents are used in these models, a value of $n = 1$ for the shale component, and for the clean sand term which value of $n = 2$.	$$S_w = \frac{1}{\phi}\left[\left\{0.81\left(\frac{R_w}{R_t}\right)\right\}^{1/n} - V_{sh}\left(\frac{R_w}{0.4\,R_w}\right)^{1/n}\right] \qquad (14)$$
Poupon and Leveaux (1971) This model is derived from the Indonesian model that demonstrates the computed water saturation change (S_w) as a function of the shaliness of the reservoir rock and resistivity of formation (S_t).	$$S_w = \left[\frac{V_{sh}^{0.5(1-V_{sh})}}{\left(\frac{R_{sh}}{R_t}\right)^{0.5} + \left(\frac{R_{sh}}{R_o}\right)^{0.5}}\right]^{-2/n} \qquad (15)$$
Schlumberger (1972) This model reflects the modified total shale model where the value $(1 - V_{sh})$ is taken into account.	$$S_w = \left(\frac{R_o V_{sh}}{2R_{sh}}\right)(1 - V_{sh}) \times \times \sqrt{\frac{R_t}{R_o}(1 - V_{sh}) + \left(\frac{R_o V_{sh}}{2\,R_{sh}}\,(1 - V_{sh})\right)^2} \qquad (16)$$

Schlumberger (1975)	$$S_w = \frac{\dfrac{-V_{sh}}{R_t} + \sqrt{\left(\dfrac{-V_{sh}^2}{R_{tsh}^2}\right) + \dfrac{\phi_T^2}{0.2\,R_t R_w (1-V_{sh})}}}{\dfrac{\phi_T^2}{0.4\,R_t R_w (1-V_{sh})}} \quad (17)$$
Juhasz (1981) This model is known as Normalised Waxman-Smith model. By using parameters that can be derived from log measurements.	$$C_t = C_w \phi^m S_w^n + (C_{sh}\phi_m^{sh} - C_w)\left(\frac{V_{sh}\phi_{sh}S_w}{\phi}\right) \quad (18)$$ C_t = conductivity of formation from deep resistivity log (s/m). C_w = formation water conductivity (s/m). C_{sh} = conductivity of shale (s/m). V_{sh} = volume of shale (m^3).
Kamel (1993) For several shaly formations, this model is virtually validated. His equation dealt with the use of clean formation resistivity (R_o) validity measurement, which showed a strong agreement with Indonesian model (1971), Modified Total shale models (1972) and Simandoux (1963).	$$S_w = \sqrt{\frac{R_o}{R_t} + \left[\frac{R_o}{R_{tsh}}\,2V_{sh}\right]^2} - \sqrt{\left[\frac{R_o}{R_{tsh}}\,2V_{sh}\right]^2} \quad (19)$$
Kamel et al. (1996) This model showed that if the Tortuosity factor (a) and cementation exponent (m) were taken into account in the *Schlumberger (1975)* concerning the formation factor (F), calculated water saturation values within a certain range of not more than 5 percent would occur instead of using only porosity.	$$S_w = \frac{V_{sh}R_t + \sqrt{V_{sh}^2 R_t^2 + \dfrac{4\,R_{sh}^2 R_t}{F\,R_w(1-V_{sh})^2}}}{\dfrac{2\,R_{sh}R_t}{F\,R_w(1-V_{sh})^2}} \quad (20)$$

Abdelrahman et al. (2000) This model provides more precise results of water saturation, achieving an interval that doesn't exceed 1 percent if *Kamel et al. (1996)* formula was updated by adding shale index (q) defined by *Alger and Raymer (1963)* as one of the seismic parameters that correspond to effective and total porosities to be equal to the term of volume of shale expressed in the equation of Kamel et al. (1996).	$$\mathrm{S_w} = \frac{\mathrm{V_{sh} R_w}\, \phi_\mathrm{E}^2}{2\,\phi_\mathrm{T}^4 \mathrm{R_t}} + \sqrt{\frac{\mathrm{V_{sh}^2 R_w^2}}{4\,\mathrm{R_{sh}^2 R_t}\, \phi_\mathrm{T}^4} + \frac{\phi_\mathrm{E}^2\, \mathrm{R_w}}{\mathrm{R_t}\, \phi_\mathrm{T}^4}} \quad (21)$$

1.3. Calculations for shale volume

The determination of shale volume is very important in the process of formation evaluation, as formation porosity and fluid content need to be calculated. If not accounted for, the presence of shale in a porous-permeable formation would typically cause manipulation in the neutron or acoustic porosity measurement and the behavior of all logs may be affected as follows (*Kamel and Mabrouk, 2003*):

1. The resistivity log will record too low resistivity value. *Hilchie (1978)* states that lowering the resistivity contrast between oil or gas and water is the most important impact of shale in a formation. The net result is that it may be very difficult, or even impossible, to decide whether a zone is productive if enough shale is present in a reservoir. *Hilchie (1978)* indicates that the shale content must be greater than 10 to 15 percent to substantially affect log-derived water saturation.
2. The neutron log response in a formation is a function of the formation hydrogen content, since shale contains different amount of water the neutron porosity in a shaly interval is a function of both shale content and the liquid filling the effective porosity.

3. By contrast, the density tool doesn't respond forcefully to most formations shale content (i.e., if the density of shale is equal to or higher than the density of matrix of a reservoir, it won't measure too high porosity). In other words, except when the shale density is greater than the density of the clean matrix, the porosity obtained by the density instrument is optimistic, but obtained porosity would be pessimistic if the density of the clean matrix is lower than shale density (*Kamel and Mabrouk, 2003*).
4. The travel time of sonic devices will increase in the case of shaly formation and this raise could be very significant in unconsolidated formations (*Kamel and Mabrouk, 2003*).

For the determination of shaliness, many log derived clay content (shaliness) indicators are usually used today. They are derived from log (resistivity, gamma-ray, or self-potential, neutron) or a combination of two logs (neutron-acoustic, density-neutron).

Reliable assessment of shale is achieved by the use of as several indicators as possible. *Worthington (1985)* and *Fertl (1978)* have presented excellent reviews of shaly formation studies.

In general, the analyst must continue with the following steps to assess the shale volume:

1. By using a single log or combination of two logs, the volume of shale can be obtained.
2. Using *Steiber (1973)*, *Clavier et al. (1971a,b)*, or *Dresser Atlas (1979)*, the proper volume of shale can be calculated.
3. Classifying the formation into shale, shaly and clean according to shale amount.
4. We should eventually identify ineffective or effective shale.
5. Calculation of Cation Exchange Capacity (CEC), which is defined as the amount of positive ions substitution that takes place per unit weight of dry rock and can be calculated using the Waxman-Smits equation (*Waxman and Smits, 1968*), which it is a function of shale volume.

2. Water resistivity and saturation determination

In 1975, Schlumberger introduced a Formula to estimate water saturation for shaly formations which can be rewritten as follows:

$$\frac{1}{R_t} = \frac{S_w^2}{F\,(1 - V_{sh})\,R_w} + \frac{V_{sh} \cdot S_w}{R_{sh}}\,. \tag{22}$$

Based on Eq. (22), the values of R_w and S_w can be estimated numerically through the following steps:

1. For each depth, R_t and ϕ are measured by any resistivity and neutron or density tool, respectively.
2. Shale resistivity (R_{sh}) is determined through the resistivity log using GR log as shown in the following Fig. 1, where shale resistivity (R_{sh}) is selected from shales between reservoir layers as the low or lowest value.
3. Shale volume (V_{sh}) is calculated and interpreted as shown in Section 1.3.
4. Formation factor (F) from Archie equation, in fully water-saturated zone, can be determined according to the following equation:

   $$F = R_o/R_w \quad \text{or} \quad F = a/\phi^m\,. \tag{23}$$

   Assume m, n, a, are known and constant.
5. Equation (22) can be used to calculate R_t for each depth by taking various intervals for both water resistivity and saturation, where:
   (a) S_w ranges from 0 to 1.
   (b) R_w ranges from 0 to 1.

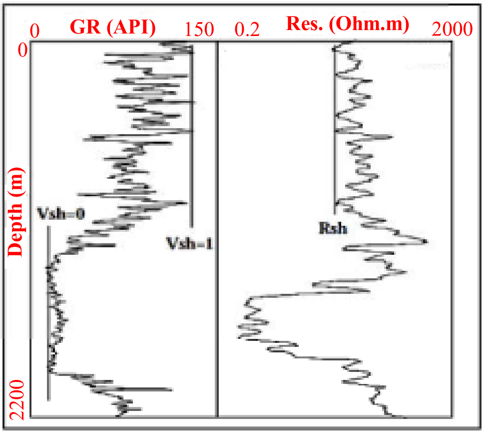

Fig. 1. Determining R_{sh} using GR and Resistivity log.

i.e., at each depth, when R_w is equal to 0.01, S_w will take different values from 0.01 to 1.00 (0.01 step), then R_w will take another value of 0.02 and S_w will vary from 0.01 to 1.00 and so on. For each calculation, R_t will be calculated using Eq. (22).

6. Comparing R_t calculated values and Rt measured value and picking the final values for both R_w and S_w corresponding to the minimum error between measured and calculated values.
7. According to step 6, we get almost 9000 values for R_t and then compare them with R_t measured at each depth. Thus, a program is designed to deal with these values and give us the final S_w and R_w.

3. Program description

Java program is used to read the input data that include R_{sh}, a, m, n values and the different values of V_{sh}, ϕ, and R_t for all depths. The program is based on three main steps:

1. The log data are digitized and placed in the format shown in Table 2.
2. For S_w and R_w, enter the intervals.
3. We have two output files, the first containing the R_t calculated for the various S_w and R_w intervals with the minimum errors and the observed standard deviation. The final S_w and R_w values could be in the second file, and these values are based on the nearest value of standard deviation observed between the output and input the resistivity and also the minimum errors between them.

Table 2. Arrangement of the input well logging data.

Column #	
Row #1	Depth
Row #2	V_{sh}
Row #3	ϕ
Row #4	R_t

4. Testing and application of the proposed techniques

The following primary concerns with the running of the proposed technique for the following:

1. Synthetic data to precisely illustrate how it can be used.
2. Real field data from Surma Basin, Bengal (Fig. 2).

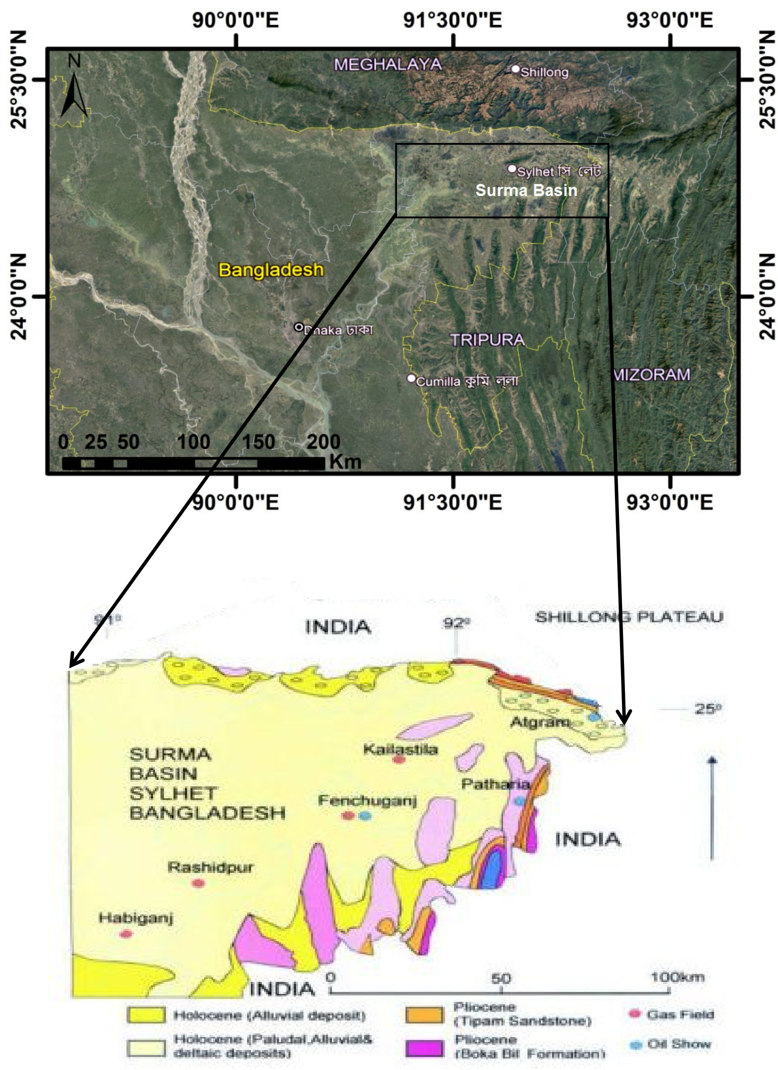

Fig. 2. (a) Regional (location) map of the study area (Surma Basin). (b) Geological map of Surma Basin, Sylhet, Bangladesh (modified after *Alam et al., 1990; Ahammod et al., 2014*).

4.1. Synthetic data

Synthetic values were used by the authors for both shale volume (V_{sh}) and R_t to determine the porosity (ϕ) from Eq. (22) after the substitution of (F) from Eq. (23) and rewrite it as follows:

$$\phi = \sqrt[m]{\frac{\left(\frac{1}{R_t} - \frac{V_{sh}S_w}{R_{sh}}\right) a\,(1 - V_{sh})\,R_w}{S_w^2}}\,, \tag{24}$$

by the use of: $m = 2.2$, $a = 0.62$ and $R_w = 0.0\ \Omega$m, $R_{sh} = 30\ \Omega$m, and $S_w = 0.3$, Fig. 3.

This way, the authors determine the real values for both water saturation and resistivity. A new program used created porosity from Eq. (22) for determining formation resistivity with different intervals for both water resistivity and saturation as indicated in Section 2.

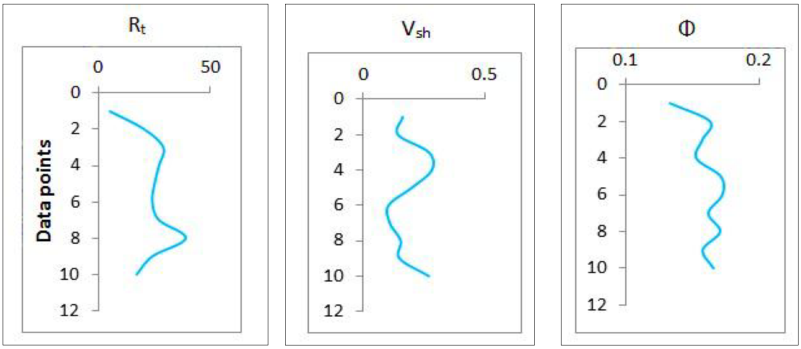

Fig. 3. Synthetic example for R_t and V_{sh} which is used to create ϕ.

By comparing the values of the synthetic resistivity and the calculated one, the S_w and R_w values corresponding to the calculated $R_{t-calc.}$ with the minimum error at each depth point are chosen to be the final and the corrected values, which range from 0.3 to 0.06 for water saturation and water resistivity, respectively.

4.2. Real field data from Surma Basin

The suggested technique is applied on Field data from Surma Basin located in the Bengal, in the North-Eastern part of Bangladesh, a Miocene gasproducing province located south of Narshingdi. All the required data to serve our objective in applying the proposed numerical technique are shown in Fig. 4.

The program used resistivity, porosity, and shale volume as input data with the required constant of R_{sh}, a, and m.

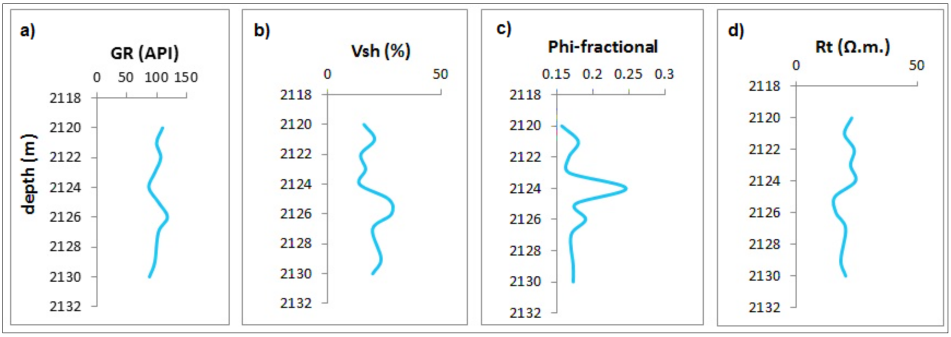

Fig. 4. Required input Data for Surma Basin, Bengal.

The program used the different intervals of both S_w and R_w, and started to run, calculate Rt_{cal} and compare them with the measured one ($R_{t,observed}$) depending on minimum error. The final values for both water saturation and resistivity are chosen as shown in Table 3 and Fig. 4.

5. Discussion

The proposed numerical technique accurately picked the final R_w & S_w values in shaly sand formations by comparing the measured and the calculated R_t to calculate the percent error as follows (Figs. 5a, 5b):

$$\mathrm{Error}(\%) = \frac{R_t \text{ measured} - R_t \text{ calculated}}{R_t \text{ calculated}} \times 100\,. \qquad (25)$$

The calculated results for S_w are compared with *Poupon and Leveaux (1971)* (Eq. (15)) & *Simandoux (1963)* (Eq. (10)) and the minimum percent error is obtained (Fig. 5c).

The calculated R_w values are compared with the measured R_w values showing high consistency with each other (Fig. 5d). The proposed approach was validated with both synthetic & real field data. The calculated RMS

Table 3. The output data from the proposed program.

Depth (m)	GR (API)	V_{sh} (%)	R_t meas. (Ω.m)	R_t calc. (Ω.m)	Error % betn. R_t meas. & R_t calc.	R_w meas. (Ω.m)	R_w select. (Ω.m)	S_w % *Poupon & Leveaux (1971)* Eq. (15)	S_w % *Simandoux, (1963)* Eq. (10)	S_w % select.
2120	110	16.1	23	22.927	0.318	0.1	0.1	42	44	44
2121	100	20.76	20	19.898	0.512	0.1	0.15	42	41	48
2122	107	14.74	24	23.5	2.124	0.1	0.17	36	36	39
2123	97	16.8	22.5	22.42	0.356	0.1	0.1	37	35	35
2124	87	14.15	24.5	24.474	0.106	0.1	0.1299	31	29	33
2125	103	26.93	16	15.959	0.256	0.1	0.1199	47	45	47
2126	118	28.17	16.5	16.458	0.255	0.1	0.17	46	53	62
2127	103	19.9	20.5	20.488	0.0585	0.1	0.067	42	42	44
2129	97	23.61	18.5	18.388	0.609	0.1	0.1099	42	40	40
2130	88	19.9	20.5	20.455	0.219	0.1	0.17	41	38	48

error using Eq. (26) was found to be 0.17 Ω.m.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (\text{measured} - \text{calculated})^2}{N}}\,. \tag{26}$$

Figure 6 shows flow chart summarizes the workflow of the newly proposed technique to estimate appropriate values for R_w & S_w in shaly sand formations.

6. Conclusion

By using inaccurate values for both water saturation and resistivity will result in overlooking producible zones. This paper introduced a complete review on water resistivity, water saturation, and shale volume calculations method, and a simple numerical method to accurately calculate R_w and S_w in shaly sand formations was also introduced; it relies on R_t calculation using different values for water resistivity and saturation and comparing the resultant value with the observed (measured) true resistivity value.

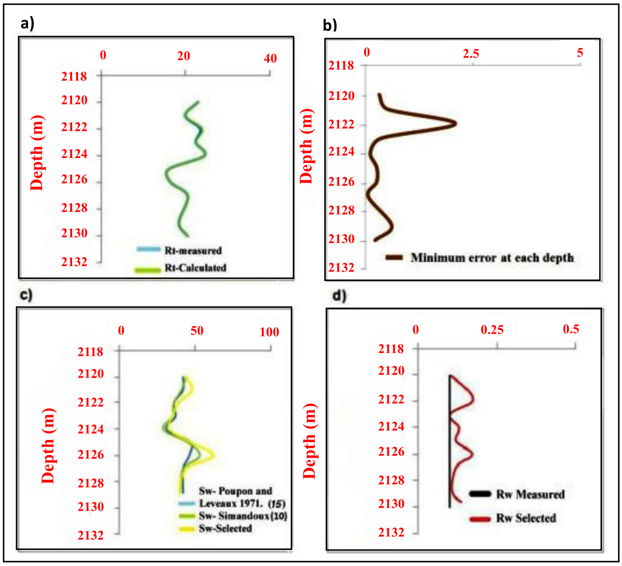

Fig. 5. (a) The measured and the calculated R_t curves; (b) Minimum error between the measured and the calculated R_t; (c) the calculated S_w from different equations and the selected S_w from the proposed technique; (d) R_w measured and the selected R_w from the proposed technique.

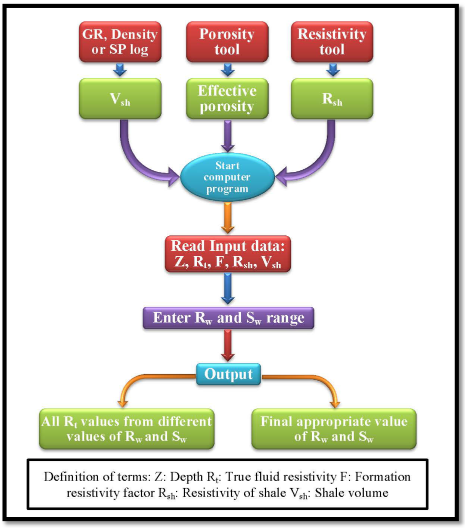

Fig. 6. Flow chart summarizes the workflow of the newly proposed technique.

Using synthetic and real data, the method is tested to reflect its ability to estimate both water saturation and resistivity with a high degree precision where the error percentage can be ignored. The researcher has also implemented a simple suggested program helping to obtain the final appropriate S_w and R_w values, and apply methodology quickly and easily where 9000 graphs must be held.

Author contributions. All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ahmed M. Metwally, Walid M. Mabrouk and Ahmed Ismail Mahmoud. The first draft of the manuscript was written by Ahmed M. Metwally, Ahmed Ismail Mahmoud and Walid M. Mabrouk commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of interests. The authors declare that they have no competing interests.

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