Jurnal Kejuruteraan 34(1) 2022: 101-108
https://doi.org/10.17576/jkukm-2022-34(1)-09

Comparison of Water Saturation Models Based on Well Logging Data: A Case Study of MX Field in Malay Basin

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Received 18 June 2021, Received in revised form 13 July 2021
Accepted 13 August 2021, Available online 30 January 2022

ABSTRACT

One of the primary methods to determine water saturation is logging measurement which uses water saturation models. Archie`s interpretation model to estimate water saturation in clean formations has successfully been useful over the years. However, in shaly sand formation this model yields inaccurate water saturation estimates due to shaly sand effects. Many shaly sand interpretation models have been developed; unfortunately; there is no unique water saturation model which works best for all formations as subsurface information may be limited and formation shaly sands may vary. Nevertheless, some water saturation models provide more accurate water saturation values for a formation. Thus, this study aimed to determine the water saturation alternative by using Dual-Water, Waxman-Smits, Indonesian, and Modified Simandoux models. The results showed that the Indonesian Model and Modified Simandoux gave the closest water saturation values with more than 80% similarities compared with logging analysis and thus should be considered the best models. Therefore, it is hoped that the findings can help improve knowledge on the selection of water saturation models best suited to the nature of formation similar to the wells, especially to other hydrocarbon exploration in the Malay Basin.

Keywords: Water Saturation Models; Well Log; Reservoir Analysis; Shaly Sand

INTRODUCTION

It is vital for reservoir engineers to characterize the rock and fluid properties in the reservoir prospect for hydrocarbon energy security especially in hydrocarbon volumetric and estimates reserve calculations. In the overall approach of the reservoir characterization, as well as equity in computation of dynamic and static reservoir modelling, water saturation is a key requirement parameter. Proper characterizing available data leads to reliable estimate of hydrocarbon in place which are to determine initial oil in place (IOIP) or original gas in place (OGIP), which represent a big challenge in all hydrocarbon exploration and development (Rashid, 2018). The characterization process can be either qualitative or quantitative (Moradzadeh and Bakhtiari, 2011). In qualitative characterization, the quality of rock was assessed through observation by operator experienced. Whereas for quantitative is applied more process in numerical characteristics such as permeability, porosity, saturation, pressure and pores sizes (Othman and Numbere, 2002). In addition, water saturation gives an idea about how much pore or void spaces filled up by water or hydrocarbon (oil and gas) in term of ratio or fraction and presenting total hydrocarbon in void space of a reservoir. In addition, it is assumed that all void spaces in a reservoir consist of either water or hydrocarbon (Dandekar, 2013) were giving the Equation (1) and (2) below:

$$Sw + Sh = 1 \quad (1)$$

$$Sw = \frac{Vw}{Vp} \quad \text{and} \quad Sh = \frac{Vh}{Vp} \quad (2)$$

Where *Sh* is the ratio of hydrocarbon saturation; *Sw* the ratio of water saturation; *Vp* volume of void space; *Vh* and *Vw* are volume of hydrocarbon and water occupied in a void space respectively.

As hydrocarbon saturation is not easy to determine, it is conventionally recommended to estimate by water saturation (Moore et al., 2011). Recently, water saturation predicted directly from effective porosity of the formation obtained from core plugs and transferred into conventional Archie's model that was developed by Archie (1942) represents in Equation (3) for resistivity logs analysis (Cai et al., 2017).

$$S_w = \frac{\sqrt[c]{\frac{R_w}{R_t}}}{\emptyset} \quad (3)$$

Where *Rw* is formation water resistivity (ohm-m); *Rt* true formation resistivity; *c* constant (sandstone – 0.9, carbonate – 1.0); *Ø* porosity.

The MX Field located in the southern part of Malay Basin (Figure 1). In 2017, the prolific Malay Basin was produced crude oil around 32% and natural gas is 26% (Noor Aziah Abd Karim, 2019). In term of lithological, the formation of reservoir in the Malay Basin is made up mainly of sandstone followed by shale that consist of clay and silt size minerals in siliclastic sequence with relatively appearance of fresh water formation (Munif et al. 2019, Gaafar et al. 2016 and Zamridin, 2014). Based on shaly sands occurrences in MX field, the existence of shale produces a discrepancy in the reservoir's total resistivity reading, causing the water saturation anticipated by Archie's equation to overestimated (Sarihi and Vargas, 2015). Furthermore, Archie's model was created primarily for clean sands (no clay minerals) but it does not account for clay minerals such as shaly sands (Worthington, 2011). Different with clean formations, conductivity in shaly sand have not contributed to water conductivity.

The extra conductivity leads to an unequal rise in conductivity in the heterogenous formation. Therefore, water saturation is an interpreted parameter that is greatly affected by the accuracy of the components of the model used in the reservoir simulation. The effect of the presence of clay on rock resistivity is dependent on content volume, type of mineral and clay distribution in rocks (Figure 2). Due to encounter shaly sand problems and economic requirement to identify water saturation practically with optimum accuracy, there are several alternative empirical models were improved such as the Indonesian by Leveaux and Poupon (1971), the Modified Simandoux by Schlumberger (1991), the Waxman-Smits by Waxman and Smits (1968) and the Dual-Water by Clavier et.al (1984). However, each models have different application in different geological region that depending on several factors which are parameters sources such as well logging and core data, distribution of shale and correlation between laboratory and empirical equations (Shedid and Saad, 2017). Thus, the intention of this paper is attempted to estimate the percentage of similarity by four alternative *Sw* models compared to actual Sw from well logging data.

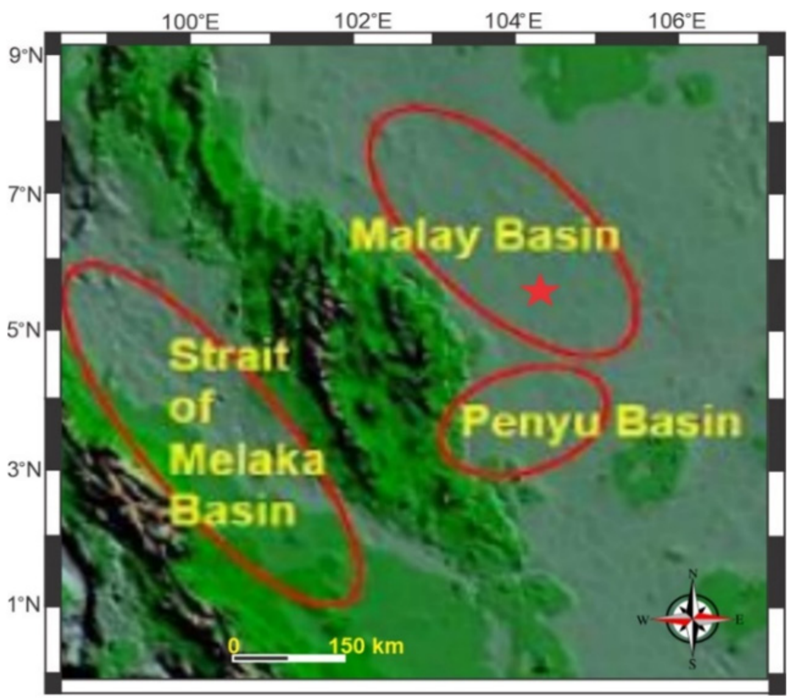


FIGURE 1. Location of Malay Basin and red star indicates location of MX-Field. (Modified after Islam et al., 2011)

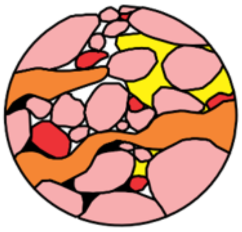


FIGURE 2. Typical shale distribution in rocks.

METHODOLOGY

INDONESIAN MODEL

The Indonesian model (Eq. 4a and 4b) has the advantage that it is applicable even if the true shale distribution in formation is unknown or uncertain. This model is best fit for reservoir with surrounding fresh water formation that has large fraction of shale volume (Al-Sudani et al. 2020).

$$\frac{1}{R_t} = \left[\frac{(V_{sh})^d}{\sqrt{R_{sh}}} + \frac{\phi^{m/2}}{\sqrt{aR_w}} \right] S_w^{\frac{n}{2}} \tag{4a}$$

$$d = 1 - \frac{V_{sh}}{2} \tag{4b}$$

Where *Rt* is average formation resistivity; Vsh shale volume fraction in rock; *Rsh* shale resistivity; *Rw* formation water conductivity; *m* rock cementation factor (1.5 - 2.0); *n* saturation exponent; *a* tortuosity constant which depends on pore geometry; *d* power factor.

WAXMAN-SMITS MODEL

The Waxman-Smits model as shown in Equation 5 is water saturation calculation that to deals with the excess conductivity introduced by clays in a total porosity model.

$$S_{wT}^{\ n} = \frac{\left(F/R_t \right)}{\frac{1}{R_w} + \frac{BQ_v}{S_{wT}}} \tag{5}$$

Where Q_v is cation-exchange capacity per unit total pore volume or effective concentration of clay counterions; BQ_v conductivity of bound water; *Rw* resistivity of formation water; *SwT* total water saturation; *F* formation factor for shaly sand; *n* saturation exponent.

DUAL-WATER MODEL

The Dual-Water model used in this study which is presented in terms of resistivity, can be written as

$$\frac{1}{R_t} = (S_{wT}\phi_t)^2 \left[\frac{1}{R_w}\left(1 - \frac{S_b}{S_{wT}}\right) + \frac{R_{sh}.\phi_{sh}.S_b}{S_{wT}} \right] \tag{6a}$$

Clarification of *Sb* and *Øt* in Equation 6b and 6c respectively below

$$S_b = \frac{V_{sh}\phi_{sh}}{\phi_t} \tag{6b}$$

$$\phi_t = \phi_e + V_{sh}\phi_{sh} \tag{6c}$$

Where *Vsh* is volume fraction of shale in the formation; *Rsh* resistivity of the shale, *Rw* resistivity of formation water; *SwT* total water saturation; *Øt* total porosity; *Øe* effective porosity; *Øsh* shale porosity.

THE MODIFIED SIMANDOUX MODEL

Schlumberger modified the general Simandoux Equation by adding $[1 - V_{sh}]$ to the denominator to account for the shaly nature inherent in the clean sands as states in Equation 7.

$$\frac{1}{R_t} = \frac{\phi^m S_w^{\ n}}{aR_w(1-V_{sh})} + \frac{V_{sh}S_w}{R_{sh}} \tag{7}$$

Where *Rt* is average formation resistivity; *m* rock cementation factor; a tortuosity constant; *n* saturation exponent; *Vsh* volume fraction of shale; *Sw* water saturation; *Rsh* resistivity of the shale.

WELL LOG DATA

Three wells from MX Field namely MX-1, MX-2 and MX-3 was used to provide actual water saturation from core and logging data were form the basis of comparison with the estimates using the four water saturation models. All cores and well logging data are donated from petroleum company and generated using Interactive Petrophysics (IP) software. Figure 3 depicts each well was evaluated and potential reservoir (sand) units were marked out using the log signature from the gamma ray log of three wells. Low gamma ray (GR), higher true resistivity readings accompanied with small crossover between density-sonic (DEN-SONIC) curves indicates that hydrocarbon type fluid is oil bearing. The presence of clays in the interval reflecting the formation Rt values to decrease slightly. The higher abnormality in resistivity measurements within the interval that could be caused by the presence of heavy minerals strikes in the porous shaly sands. The shaly sand section in MX-1 well identified at depth range 2135 ft to 2215 ft, MX-2 corresponding to the depth of 2390 ft to 2463 ft and for MX-3 from 4009 ft to 4077 ft.

Furthermore, the percentage of V_{sh} need to identify first. The GR log is the most common shale volume indicator and it responds to changes emitted by formation in natural radiation. The GR log does not measure the volume within the shales of silts or other inclusions. The maximum response of gamma rays is taken as the shale point and as the clean sand point the minimum response. The GR clay indicator can be calculated using the following Equation 8.

$$V_{sh} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (8)$$

Where GR_{log} is gamma ray reading from formation; GR_{min} minimum gamma ray reading usually carbonate or clean sand; GR_{max} maximum gamma ray reading (shale).

SIMILARITY PERCENTAGE

The calculated *Sw* values of all the four models are then compared with the *Sw* values obtained from log analysis and ascertain the best model suitable to be used in the field. The constant reservoir rock properties parameters extracted from three of the MX wells were used to compare with *Sw* models as tabulated in Table 1. The *Sw* estimates from each model are determined and compared to the value from logging analysis which is taken to identify percentage of similarity (Equation 9) due to the robustness of the collection log data. More than 80% similarity describes as excellent model, 79% to 60% is fair and lower than 59% is poor to the actual case study. The statistical analysis included correlation coefficient (R^2) and root mean square error (RMSE) were applied to quantify the quality of calculated *Sw* models with actual *Sw*.

$$Similarity\ (\%) = \frac{Average\ Sw\ Model}{Average\ Sw\ Log} \times 100\% \quad (9)$$

TABLE 1. Constant reservoir parameters of MX Field in Malay Basin.

Constant Parameters MX Field (unit)	Value
$Ø_{sh}$ (ratio)	0.09
R_{sh} (ohm-m)	1.7
R_w (ohm-m)	0.0811
R_t (ohm-m)	2
m (dimensionless)	1.33
n (dimensionless)	1.77
a (dimensionless)	1.65
F (dimensionless)	8.0
BQ_v (s/m)	0.0072

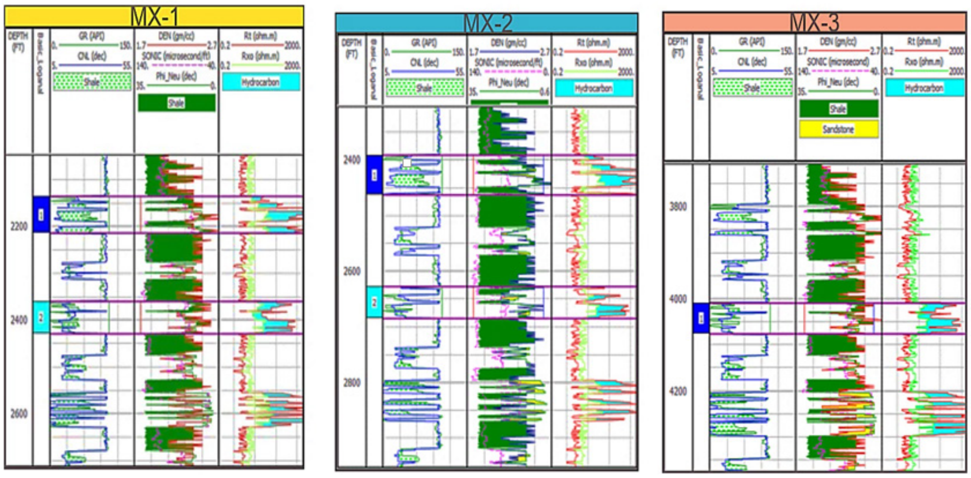


FIGURE 3. Log interpretation from three wells in MX Field at different depth shows shaly sand formation (blue navy) based on gamma-ray logs (GR), density-sonic log (DEN-SONIC) and resistivity log (Rt).

RESULT AND DISCUSSION

SHALY SAND CONTENT

Figure 4 depicts the model of laminated shale with a decrease in effective porosity and increase in volume of shale. This lamination is as a result of fine-grained particles settling within deposited sediments forming fine lamina across the formation and discrete thin layer in between sandstones. The pore spaces connectivity are shows reduced due to the presence of shale lamina which are reduces the porosity of the sand and it bring about decrease in its resistivity when the presence of shale properties as suggested by Patrick et al., (2018). Thus, the cross-plot analysis confirmed that shaly sand occurs in selected depth ranges of each well.

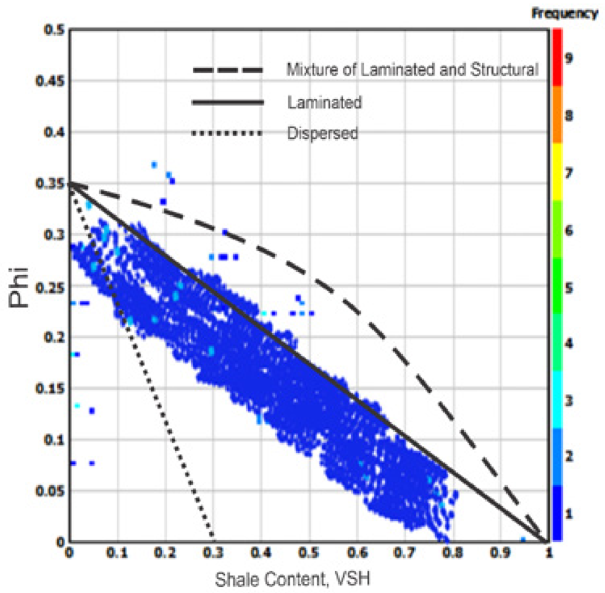


FIGURE 4. Cross-plot of effective porosity against Vsh based on selected depth of the three wells.

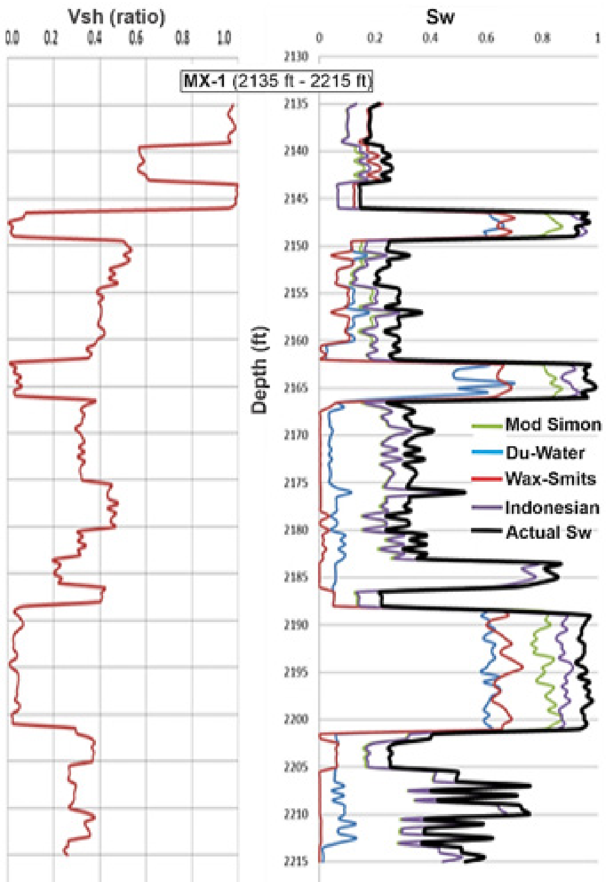
APPLICATION WATER SATURATION MODELS IN MX FIELD

Case 1: MX-1 Well

The values of the estimated *Sw* for the four models as compared to actual *Sw* and *Vsh* in MX-1 well are presented in Figure 5. All four models almost matching responsiveness and pattern to the *Vsh* and remaining shaly sand water saturation models. The Indonesian model exhibits the highest values of *Sw* similarity with 84 % while the Modified Simondoux model provided exceptionally in the highest value ranges. At the same time, the Dual-water model showed slightly higher values of *Sw* than Waxman-Smits. Besides that, the Indonesian model gave estimates closest to values derived from actual *Sw* and should be considered the best model at this layer. In addition, the Waxman-Smits model gave estimates that are comparatively lower and becomes the most unfit or poor model for *Sw* calculation in MX-1 well.

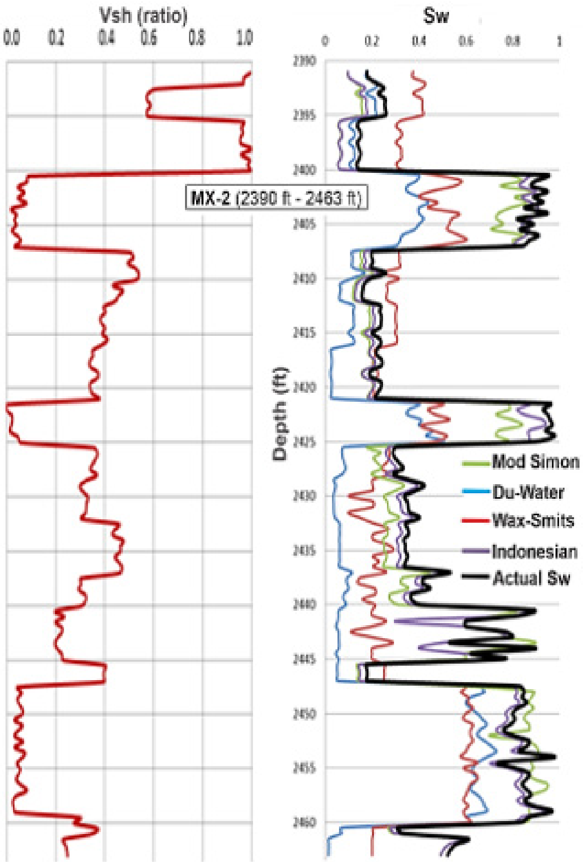
Case 2: MX-2 Well

Figure 6 shows a comparison between the *Vsh* and *Sw* values using four different models as a function of depth in the shaly sand zones at the depth ranges 2390 ft to 2463 ft of the MX-2 well. The Dual-water model yielded the lowest values with 46 percent as compared with actual *Sw* values while the Indonesia model provided exceptionally the highest values (92%). Furthermore, the Modified Simandoux model showed slightly lower values than Indonesian followed by Waxman-Smits. Nevertheless, the Indonesian model and Modified Simandoux model gave approximately similar estimation. Overall, all four models followed an almost similar responsiveness and pattern to the *Vsh*. For this well area, the Indonesian model gave estimates closest to values derived from logging analysis and should be considered the best model at this shaly sand formation while the Dual-water model gave estimates that are comparatively lower and becomes the most unsuitable model.



Sw Model	Average Similarity (%)
Modified Simondoux	78
Dual-Water	44
Waxman-Smits	42
Indonesian	84

FIGURE 5. Trend comparison of Vsh in between Sw models and actual Sw for MX-1 well.

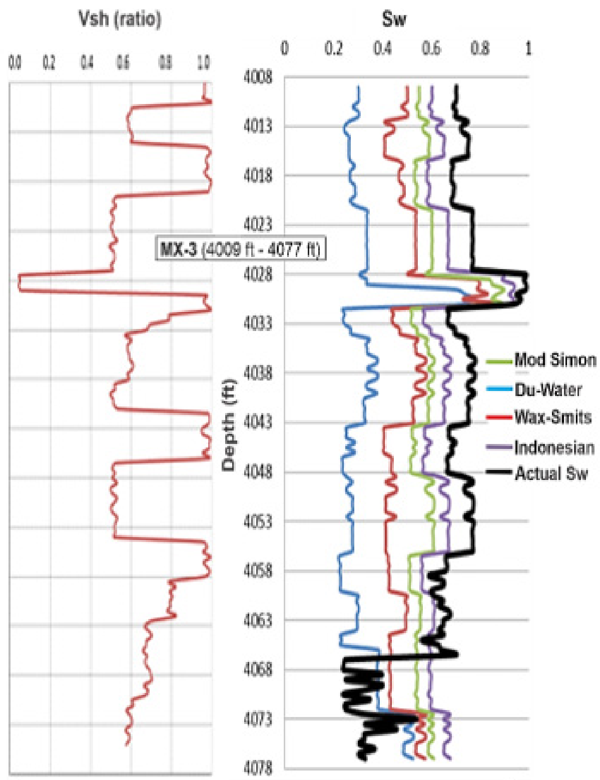


Sw Model	Average Similarity (%)
Modified Simondoux	90
Dual-Water	46
Waxman-Smits	72
Indonesian	92

FIGURE 6. The Sw models trend compared with *Vsh* and actual *Sw* for the MX-2 well.

Case 3: MX-3 Well

Figure 7 depicts the values of the *Vsh* and estimates for the four models as compared to the actual *Sw* derived from logging analysis for shaly sand formation in the MX-3 well. Moreover, the Indonesian model yielded highest similarities of Sw with 96% and the Dual-water model at the lowest values with 49%. As for the same graph, Modified Simandoux model showed slightly lower values than Indonesian, followed by Waxman-Smits model. On the other hand, all four models followed an almost alike responsiveness and pattern to the *Vsh* and remaining shaly sand water saturation models to the actual *Sw* values except from the deeper depth ranges of the layer at 4067 ft to 4078 ft. Drastic decrease in water saturation reading for logging analysis at deeper depth suggested as decrease in shale fraction formation were proven with no reaction from all four models with shale distribution plot in the depth. Another reason may be due to the accuracy of data obtained or because this layer is the dispersed shale region, the distribution of shale is not uniform. Dispersed shale is only concentrated in a few small locations in the formation, but at those locations, the *Sw* value is largely reduced.



Sw Model	Average Similarity (%)
Modified Simondoux	87
Dual-Water	49
Waxman-Smits	73
Indonesian	96

Selection Water Saturation Model

FIGURE 7. Trend comparison between *Vsh* with calculated curve by *Sw* models and actual *Sw* for the MX-3 well.

Figure 8 illustrates a distribution of the comparison between calculated and actual Sw collected from 2000 readings based on three wells in MX field. The red line illustrating in the figure indicates that calculated and actual at the same similarity (100%). The Indonesian model data it can be seen uniformly distributed were close to the red line and followed by the Modified Simondoux data. However, the Waxman-Smits differs slightly with actual Sw data, following by the Dual-water not in well agreement with the red line and scattered indicating calculation are poor coverages.

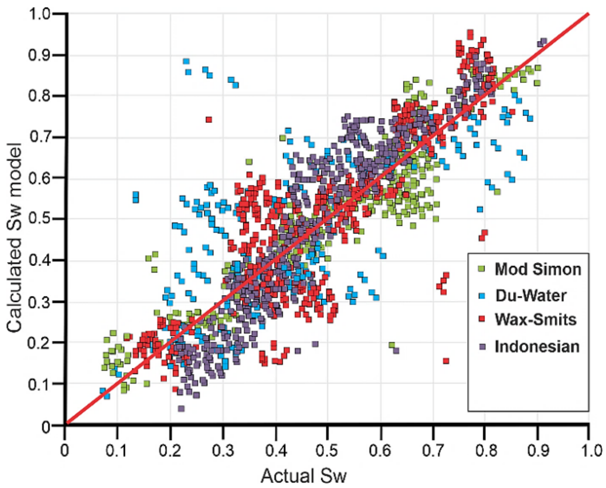


FIGURE 8. Distribution of *Sw* calculated from models and actual value based on three wells.

In order to strengthen the quality of the quantitative assessment, the study applied inferential statistics including Rmse and R^2 as shown in Table 2. The findings indicate that the Indonesian and Modified Simondoux model are the most suitable which are close to the actual *Sw* with highest R^2 and lowest Rmse.

TABLE 2. Inferential statistics between the models and actual Sw from logs reading.

Models	Rmse	R^2
Modified Simondoux	0.0072	0.9305
Dual – Water	0.0911	0.6732
Waxman – Smits	0.0103	0.7025
Indonesian	0.0018	0.9787

* Generated from 2000 readings

For each of the well, summary of selection results is listed in Table 3.

TABLE 3. List of selection results of *Sw* model.

Well	Model of Choice
MX-1	Indonesian
MX-2	Indonesian & Modified Simandoux
MX-3	Indonesian & Modified Simandoux

CONCLUSION

In conclusion, the Indonesian and Modified Simandoux models are suitable to be used to calculate water saturation in Malay Basin provided that proper adjustments are made for the shaly sand content. The *Sw* values obtained from these two methods are within acceptable range which is 80% similarities to actual *Sw*. Overall, the *Sw* values from these models almost fluctuated in the same way as the logging analysis.

The model which gives the closest value to actual *Sw* is the Indonesian model. The equation is selected based on the characteristics of the formation surroundings which are similar to both these locations; laminated and dispersed shale distribution and clean formation water surroundings. It is found that there is no direct relationship or same pattern to actual water saturation value from readings of logs. The high estimated value using the Indonesia and Modified Simandoux is mostly attributed to the constant reservoir parameters in both models which are *m* (1.33) and *n* (1.77). This indicates that proper estimation of *m* and *n* values has affected on the prediction of water saturation model.

Thus, it is suggested that the study continued by comparing models with other neighbor fields to be more accurate in suitability of the Indonesian and Modified Simondoux equations. Additionally, the sensitivity analysis for exponent *a, m* and *n* constant need to take account in order to reduce overestimation in future study. However, it is hoped that evaluation of initial water saturation from well logging and estimation of field reserves can be improved for future hydrocarbon exploration especially in Malay Basin.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Teknologi Malaysia especially for petroleum engineering department to provide data bank reservoir and geology programme in Universiti Kebangsaan Malaysia in transfer sharing knowledge programme. This mutual support dedicated work from Ms. Raja Johannes, the Royal Award recipients in 2019 during the 63rd UTM Convocation.

DECLARATION OF COMPETING INTEREST

None.

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