CHOICE OF WATER SATURATION MODEL IN LOG ANALYSIS AND ITS IMPLICATION TO WATER SATURATION ESTIMATES – A FURTHER INVESTIGATION

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ABSTRAK

Saturasi air adalah salah satu faktor penting dalam estimasi akumulasi dan cadangan hidrokarbon. Kesalahan dalam estimasi saturasi air akan menimbulkan bias yang cukup berarti atas kedua besaran tersebut. Meskipun diketahui bahwa ada beberapa faktor yang dapat menimbulkan kesalahan dalam estimasi saturasi air, pemilihan model saturasi air diperkirakan memainkan peranan yang penting. Studi ini melibatkan delapan model saturasi air yang tetap banyak dipakai sampai sekarang. Dengan menggunakan data masukan yang sama terbukti bahwa model-model tersebut menghasilkan estimasi saturasi air yang bervariasi. Dengan perbedaan harga saturasi sebesar 20% saja maka kesalahan yang dihasilkan atas estimasi cadangan dapat mencapai 50%, bahkan lebih, terutama jika dilihat lebarnya potensi perbedaan harga saturasi air yang dihasilkan oleh model-model tersebut. Bukti-bukti yang dihasilkan dari studi ini seharusnya dapat memperkuat kesadaran kita akan kemungkinan adanya kesalahan tersebut di atas dan menjadikan kita menjadi lebih berhati-hati dalam memilih model saturasi.

Kata kunci: saturasi air, pemilihan model saturasi air, kesalahan angka cadangan, kehati-hatian dalam penerapan model

ABSTRACT

Water saturation is one of the most important governing factors in hydrocarbon in place and reserves estimation. Error in the estimation of water saturation may significantly impose bias in the estimation of both quantities. In spite of there are various factors affecting potential error in water saturation estimation, choice in water saturation model(s) appears to play an important factor. This study involves eight water saturation models that are widely used in log analysis up until today. Using the same input data, the eight models have proved themseleves to have produced different water saturation estimates. Using a moderate level of water saturation error of 20% evaluation may result in up to 50% error in the reserves estimates. Observing the wide disparities in the estimated water saturation values yielded by the models used in this study, errors higher than 50% may take place. This evidence should strengthen our awareness over the potential error and careful applications of model(s) – and validation of results – that have to be observed.

Keywords: *water saturation, choice of water saturation model, error in reserves, careful application of model*

I. INTRODUCTION

Water saturation is an important parameter in the determination of hydrocarbon in-place in reservoir. Uncertainty in the water saturation data results in uncertainty in the estimates of hydrocarbon accumulation and reserves (Oil & Gas Journal, 2004). However, as Worthington put it earlier (Worthington, 1985), log interpretation problem of water saturation determination is that each model can provide significantly different values. The problem is still in place at present. Despite the known problem, log interpretation of today is still often carried out without any concern over the problem and the resulting biased estimates remain being used faithfully for hydrocarbon in place eatimation.

Widarsono (2008) also discussed this implication on estimation of hydrocarbon in place. In the study Archie model plus four other shaly sand water saturation models to provide varried sets of water saturation estimates. The shaly sand water saturation models used were Popon dkk (1953), Hossin (1960), Simandoux (1963), and Fertl (1975). Despite deterministic in nature these old mathematical expressions are still commonly in use at present. The study showed that different use of water saturation model may lead to different sets of water saturation estimates. Provided no validity check is made this certainly leads to bias in the estimates of hydrocarbon in place.

Despite the differences, the study reported in Widarsono (2008) has also shown that results of some water saturation models may also prove that they tend to yield similar estimates in certain ranges of shale contents and formation rock resistivity. To understand this occurrence a further investigation has been performed using a couple of other models of Schlumberger (1975) and Dual Water (Bassiouni (1994) plus the more recent model of Kamel and Mabrouk (2002), and the results are combined with the previous results in order to provide a broader view over the issue. As in the case of Widarsono (2008), this paper is not intended to determine which water saturation model as the best and most reliable, but instead with these additional water saturation models being used it is hoped that this may enrich our awareness about what the different models could mislead.

II. WATER SATURATION MODELS

Following the investigation and study made by G.E. Archie in 1942 – resulting in the infamous Archie water saturation model – scores of water saturation models have been constructed and proposed, especially those for application in shaly sand cases. In the case of shaly sand water saturation model, each of the models was constructed based on various assumptions such as clay structures and presence of multiple formation water. Despite the underlying conditions for model validity the models are often used indiscriminately for any cases of shaly sands with varying outcomes. Therefore, no special attention is to be given to the matter in this study, and water saturation estimates are the sole outcomes that are required.

Applications of the models have been reported in many articles, but there were rarely reports showing the models used simultaneously. It is the interest of this study to observe the hypothetical application of some of those models and to be aware of the differences and the similarities. In Widarsono (2008), the Archie water saturation (S_w) model of

$$S_w{}^n = \frac{a}{\phi^m}\frac{R_w}{R_t} \qquad \text{....................... (1)}$$

was used as the primary source of comparison, with n, a, ϕ, m, R_w, and R_t are saturation exponent, tortuosity, porosity, cementation factor, formation water resistivity, and formation resistivity, respectively. The shaly sand models used in the study were the Poupon *et al.* (1953) laminated shaly sand model of

$$S_w{}^n = \frac{a}{\phi^m}\left[\left(\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}\right) \times \frac{R_w}{(1-V_{sh})}\right] \qquad \text{.......... (2)}$$

with V_{sh} and R_{sh} are respectively the shale contents and shale resistivity, the Hossin (1960) dual parallel conductance (sand – shale) model of

$$S_w{}^n = \frac{a}{\phi^m}\left(\frac{1}{R_t} - \frac{V_{sh}{}^2}{R_c}\right)R_w \qquad \text{.......... (3)}$$

with dispersed clay resistivity R_c = 0,4 x R_{sh}, the Simandoux (1963) dispersed clay model of

$$S_w = \frac{0{,}4R_w}{\phi}\left[-\frac{V_{sh}}{R_{sh}} + \sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2 + 5\left(\frac{\phi^2}{R_t R_w}\right)}\right], \quad \text{... (4)}$$

and the Fertl clay distribution-free model of

$$S_w = \frac{1}{\phi}\left[\sqrt{\frac{0{,}81 \times R_w}{R_t} + \left(\frac{\alpha V_{sh}}{2}\right)^2} - \frac{\alpha V_{sh}}{2}\right] \qquad \text{.......... (5)}$$

(for a = 0.81, m = 2, dan n = 2) with α is a measure of correction on density and acoustic log data and with values ranging from 0.15 though 0.36.

In this study, in addition to results yielded by the five water saturation models, results from two other models are also presented. The first of the three additional models is the Schlumberger (1975) dispersed-clay model of

$$S_w = \frac{0,4R_w(1-V_{sh})}{\phi^2}\left[-\frac{V_{sh}}{R_{sh}} + \sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2 + 5\left(\frac{\phi^2}{R_t R_w (1-V_{sh})}\right)}\right]. \quad \text{... (6)}$$

Notice the similarity to the Simandoux model.

The second additional model is the Dual Water (DW) model. As described by Asquith and Krygowski (2004), the Dual Water model is perhaps the most widely used of the techniques that go beyond the shale-volume methods. The DW model of

$$S_{wt} = b + \sqrt{b^2 + \frac{R_w}{R_{wa}}} \quad \text{...................... (7)}$$

recognises the presensence of two kind of water in the shaly rocks, the free water and the bound water (i.e. water bound in the clay within the rock), both of which influence the overall reading of the true formation resistivity (R_t). The basic idea of the model's application is to find the saturation of the free water (S_{we}). In the Equation (7) S_{wt} and R_{wa} are total water saturation (shale corrected) and apparent water resistivity, and

$$b = \frac{S_{wb}\left(1-\left(R_w / R_{wb}\right)\right)}{2} \quad \text{.................... (8)}$$

with S_{wb} and R_{wb} are saturation and resistivity of bound water. The bound water resistivity is determined from the nearby shale formation and the bound water saturation is estimated using

$$S_{wb} = \frac{\phi_{wb}}{\phi_t} \quad \text{.................... (9)}$$

Where ϕ_{wb} and ϕ_t are porosity filled with bound water and total porosity, repectively. Upon knowing the Swb, the effective free water saturation (Swe) is calculated using

$$S_{we} = \frac{S_{wt} - S_{wb}}{1 - S_{wb}}. \quad \text{...................... (10)}$$

The third additional model is the Kamel and Mabrouk (2002) model. The model is a combination of Archie and Raiga formulas (Alimoradi *et al*, 2011) with using two logs of acoustic and electrical resistivity of

$$S_w = \sqrt[m]{\frac{aR_w}{\left[1-\left(\frac{V_p \Delta t_{ma}}{10^6}\right)^{\frac{1}{X}}\right] R_t}} \quad \text{......... (11)}$$

where V_p and Δt_{ma} are P-wave velocity in rock obtained from acoustic log and the P-wave acoustic transit time of the rock matrix, respectively. Unlike the shale-volume correction type models, this model introduces X as additional conductivity added by clay. The effect of the conductivity in overall is a combination between this factor and V_p, which reflects the shale quantity relative to matrix velocity of V_{ma} (= $1/\Delta t_{ma}$). The values of X are proposed as 1.6, 1.76, and 2.0 for sandstone (quartz), limestone (calcite), and dolomite, respectively.

III. RESULTS OF MODEL APPLICATION

In a manner similar to the study in Widarsono (2008) a set of the same hypothetical data as used in the Fertl model is used. This data covers:

Water resistivity (R_w) = 0,1 Ohm-m

Tortuosity (a) = 0,81 (Tixier)

Cementation factor (m) = 2 (Tixier), and

Saturation exponent (n) = 2

Shale resistivity (R_{sh}) = 1 Ohm-m

Additional data:

Bound-water resistivity (R_{wb}) = 0.05 Ohm-m (for Dual Water model)

Clay-added conductivity factor (X) = 1.6 (sandstone, for Kamel-mabrouk model)

P-wave transit time in matrix (Δt_{ma}) = 160.4 µsec/m (sandstone, for Kamel-Mabrouk model)

P-wave velocity (V_p) data for Kamel-Mabrouk model is created through the use of Wyllie time-average model of

$$\phi = \frac{\Delta t_p - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}.$$

using P-wave transit time in fluid (Δt_f) of 576 µsec/m and $V_p = 1/\Delta t_p$.

Similarly too to Widarsono (2008), for porosity (ϕ) and shale contents (V_{sh}) a value set of 10%, 20%, dan 30% is used. Porosity values of higher than 30% are not used since they are likely to be associated with low shale contents and – therefore – similar water saturation estimates. Shale contents higher than 30% are not used either, since rocks with these high shale contents are usually regarded as no longer belonging to productive reservoir rocks.

Figures (1) through (9) present results of water saturation estimates for the eight water saturation models, for rock resistivity values of from 1 Ohm-m to 70 Ohm-m. The low resistivity values of lower than 5 Ohm-m are used in order to asses the potential given by the seven shaly sand models in correcting the Archie model. On the other hand, the higher resistivity values of higher than 10 Ohm-m are used to observe the differences in the water saturation estimates.

From the plots between rock resistivity and water saturation, it is obvious that at lower resistivity values correction on the Archie model is not significant especially for moderate porosity (around 20%) and moderate-high porosity (30%). Any corrections made by the shaly sand models still keep the water saturation at high values of higher than 70%. At those high water saturation levels, the rocks are usually still regarded as water-bearing.

As in the case of the four shaly sand models used in Widarsono (2008), the additional three shaly sand models used in this study also show significant difference in water saturation for resistivity values higher than 10 Ohm-m. As an extreme case, plots in Figure (9) show that while Archie model produces 90% water saturation for resistivity of 11 Ohm-m the Kamel-mabrouk model yields a corrected water saturation value of down to 18%. Larger discrepancies are even shown by Hossin and Poupon models for lower resistivity values. On the other hand, the two additional models of DW and Schlumberger appear to produce corrections in lesser degrees.

From the four shaly sand models used in Widarsono (2008), Fertl and Simandoux models tend to produce similar estimates even though discrepancies occur for low porosity (10%), as depicted on Figures (3), (6), and (9). Despite the similarity shown by the results produced by the two models, it is worth noting that the two models have been derived under different principles (see Dresser Atlas, 1982). One of the cause is most likely due to the choice of $\alpha = 0.25$ for the Fertl model even though in general the values range between 0.15 and 0.36. Similar occurrence also takes place between Poupon and Hossin models.

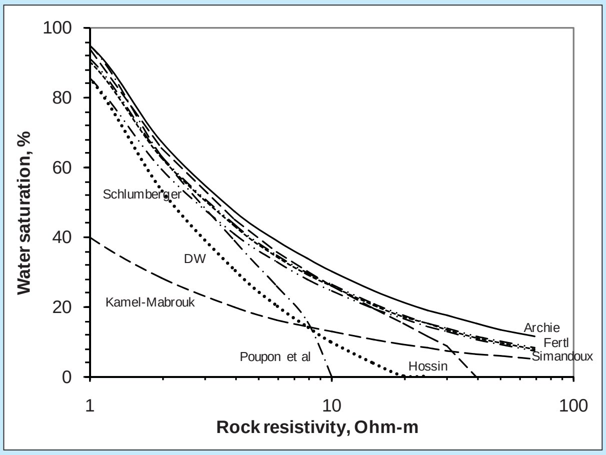

Figure 1
Plot for the eight water saturation models, with Vsh = 10% and porosity = 30%. Note: shale volume fraction is for Poupon *et al*, Hossin, Simandoux, Fertl, and Schlumber models only.

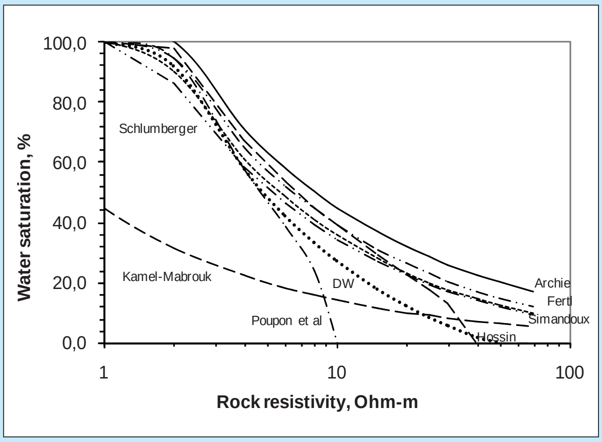

Figure 2
Plot for the eight water saturation models, with Vsh = 10% and porosity = 20%. Note: shale volume fraction is for Poupon *et al*, Hossin, Simandoux, Fertl, and Schlumber models only.

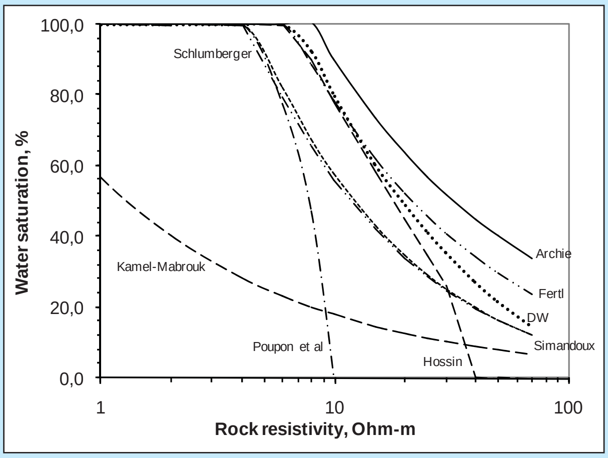

Figure 3
Plot for the eight water saturation models, with Vsh = 10% and porosity = 10%. Note: shale volume fraction is for Poupon *et al*, Hossin, Simandoux, Fertl, and Schlumber models only.

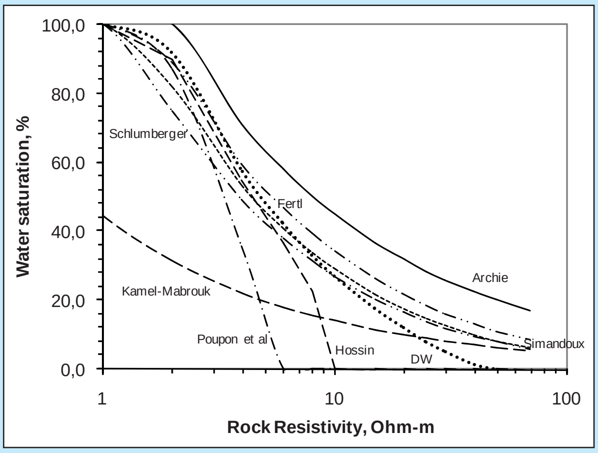

Figure 5
Plot for the eight water saturation models, with Vsh = 20% and porosity = 20%. Note: shale volume fraction is for Poupon *et al*, Hossin, Simandoux, Fertl, and Schlumber models only.

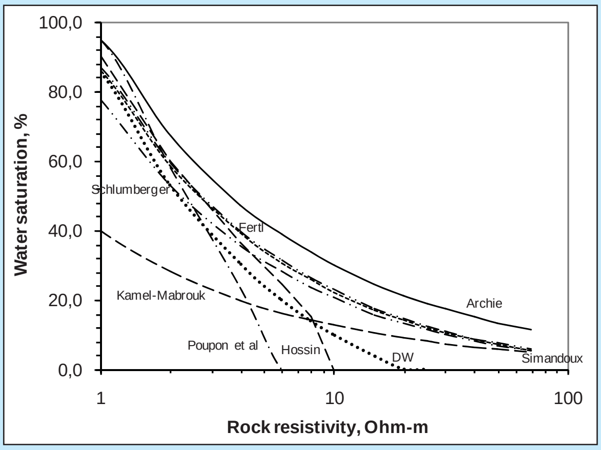

Figure 4
Plot for the eight water saturation models, with Vsh = 20% and porosity = 30%. Note: shale volume fraction is for Poupon *et al*, Hossin, Simandoux, Fertl, and Schlumber models only

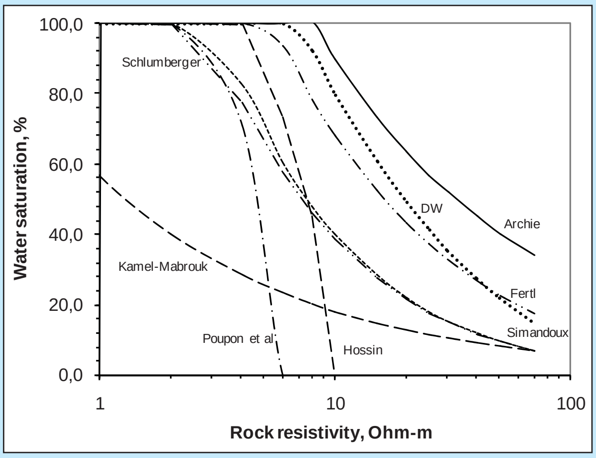

Figure 6
Plot for the eight water saturation models, with Vsh = 20% and porosity = 10%. Note: shale volume fraction is for Poupon *et al*, Hossin, Simandoux, Fertl,

For three additional models, the Schlumberger model appears to perform in a similar manner to the Simandoux model, this can be understood considering the similarity between the two models (Equations (4) and (6), both are dispersed-clay model. The DW model in general provides moderate corrections at lower resistivity values but becomes at higher resistivities. However, the magnitude of the correction is not neccessarily the norm since the input parameters of R_{wb} and ϕ_{wb} for the DW model are simplification and only assumption. For the Kamel-Mabrouk model, considerable corrections on Archie model occur at rock resistivity values of less than 1 Ohm-m. Assuming the input parameter for the model as real it can then be considered that this model works well for low resistivity zones with their potential of being overlooked. Nevertheless, a more thorough investigation has to be performed for a better conclusion.

Regardless whether the models used are the old ones or the newer models, it has been shown that the estimated water saturation values remain varied and without careful checks through the use of production test data and others the water saturation estimates still have the potential for misleading the estimation of hydrocarbon in place. Observing the variation of the water saturation values produced – in spite of the same data being used – hundred percents of error may result in the estimation of hydrocarbon in place. This is not to take into consideration of other sources of error such as in uncertainties in the determination of porosity distribution and bulk reservoir volume. This underlines that a careful choice of water saturation model that suites to the reservoir rock condition is of utmost important, regardless the principle under which the model is derived.

IV. EFFECT OF DIFFERENT ESTIMATES ON RESERVES

In a manner similar to the study in Widarsono (2008), a brief investigation is made on the effect of different water saturation estimates on hydrocarbon in place and reserves. Earlier than the study presented in Widarsono (2008), a similar study has also been carried out (Oil & Gas Journal, 2004). Figure 10 presents one aspect of the study, among which is a relation between error in water saturation (20% error is assumed) versus the error that can be potentially inflicted on the reserves.

Suppose that a reservoir has average water saturation of 30%, then with the error of 20% in the water saturation estimates – due to the non-validated use of different water saturation models – this could inflict error in reserves of about 27%. For higher water saturation values the error is likely to be higher, with actual water saturation value of 60% can lead to around 50% error in the reserves. This is understandable since at higher water saturation values the reserves values are consequently lower and therefore more vulnerable to error in the estimation.

The lesson from the use of relation on Figure 10 is clear, even though the cause of error in the estimation of water saturation is not limited to the choice of water saturation model only. As shown in the same publication, factors such as wrong input in cementation factors and saturation exponent may also affect the water saturation estimates. Nonetheless, the vast disparity between the estimates shown on Figures (1) through (9) indicates that choice in water saturation model is also important, and even larger errors in resrves than are shown in Figure 10 may take place because of this factor.

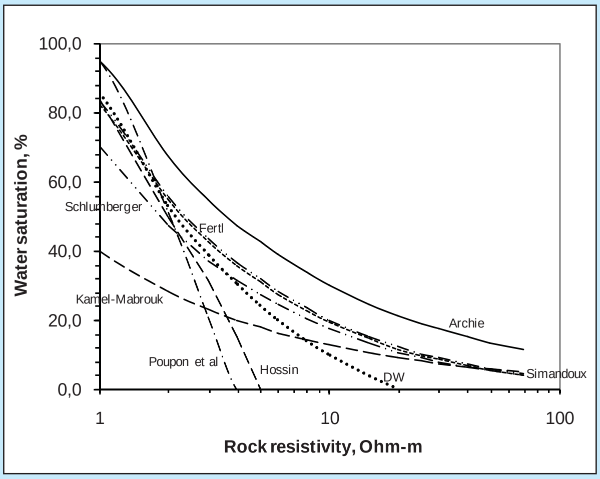

Figure 7
Plot for the eight water saturation models, with Vsh = 30% and porosity = 30%.
Note: shale volume fraction is for Poupon *et al*, Hossin, Simandoux, Fertl,

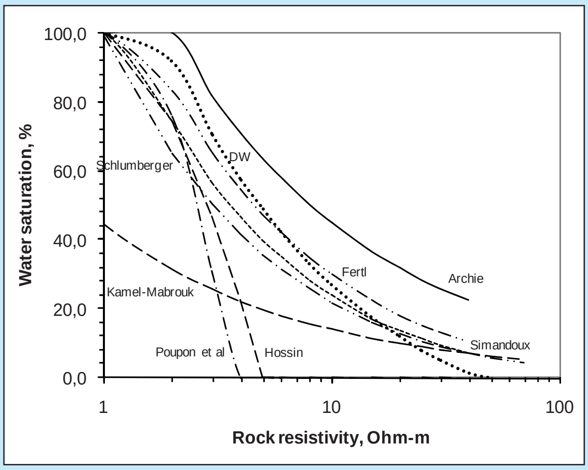

Figure 8
Plot for the eight water saturation models, with Vsh = 30% and porosity = 20%.
Note: shale volume fraction is for Poupon *et al,* Hossin, Simandoux, Fertl, and Schlumber models only

V. DISCUSSIONS

Choice for the most correct water saturation model in conventional open-hole well-log analysis is dependent on the stage of development of a field of concern. In initial stage (discovery) and the subsequent reservoir delineation activities log analysis tends to use whatever water saturation model considered appropriate. However, in later stages of field development – when more data has been obtained – a more careful choice in water saturation model has to be made.

Information regarding lithology and shale distribution has to be at disposal. This is true since many of the shaly sand water saturation models have been derived based on assumptions made on this matter. The best source of information is visual data obtained by direct observation on core samples through petrographic analysis. Use of Archie model is appropriate for clay-free sandstones and carbonates while detection over clay distribution type and presence of secondary microporosity certainly point to the most appropriate model(s). For shaly sands with no clear distinction over the predominated shale distribution type, some models such as Alger (1963) and Fertl (1975) can be used as standard models.

For low resistivity rocks (R_t < 5 Ohm-m), or often termed as 'overlooked zone(s)' the choice over the most appropriate water saturation model can be considered as not as crucial as in the case hydocarbon-bearing rocks with higher resistivities. For low resistivity rocks, different use of water saturation models leads in general to whether or not the 'overlooked zone(s)' can be detected. For higher resistivity hydrocarbon-bearing rocks, however, a mistake in choosing the right model leads to significant error in the estimation of hydrocarbon in place. The use of newer Kamel-Mabrouk model seems to underline this further since the model provides considerable corrections to Archie model at this low resistivity region. However, again, a more careful and deeper investigation has to be spent for a better understanding.

After choosing the most appropriate water saturation model, whenever supporting data permits, it is not necessarily true that all outcomes of the analysis can be regarded as correct and representative to the in situ condition. Apart from the fundamental shortcomings of the models themselves there are other sources of error such as log data quality, assignment of support data, and the means used to distribute the water saturation in three dimension and at greater scale (i.e. reservoir scale). The choosing of the most appropriate water saturation model with regard to the formation rock condition will indeed reduce the uncertainties in the estimation of water

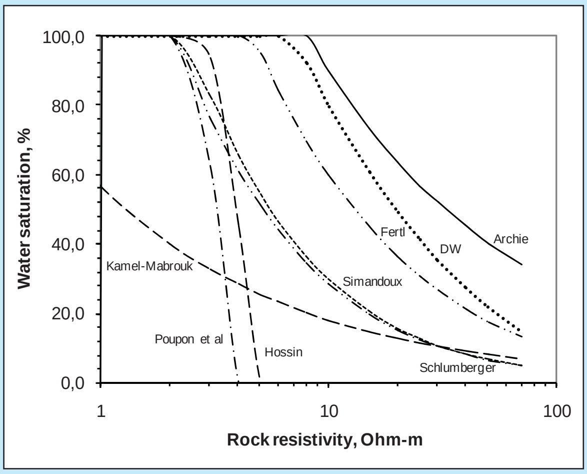

Figure 9
Plot for the eight water saturation models, with Vsh = 30% and porosity = 10%.
Note: shale volume fraction is for Poupon *et al*, Hossin, Simandoux, Fertl, and Schlumber models only.

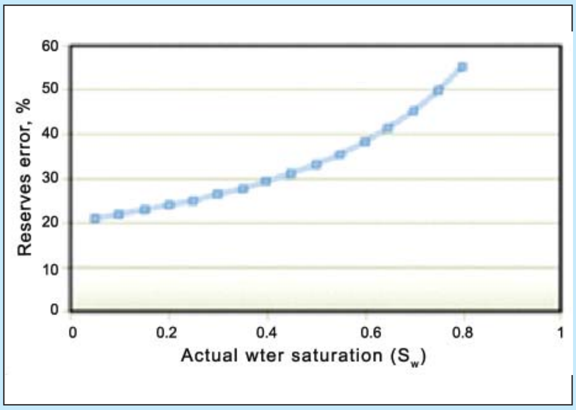

Figure 10
The effect of error in water saturation (assumed 20%) on error in the resulting reserves estimates. The x-axis is the actual average value of water saturatin in reservoir (Oil & Gas Journal, 2004)

saturation. Nevertheless, as have always been shown by real practices, no matter how sophisticated a water saturation model could be good input, data and sources of validation (e.g. well testing and core tests) is always needed.

VI. CONCLUSIONS

From this study, a set of main conclusions have been drawn:

1. An inappropriate choice of water saturation model may result in considerable bias in the resulting water saturation estimates even at conditions that all supporting data used are the same. Provided no checks and corrective actions are taken the bias can result in gross overestimation or underestimation over the hydrocarbon accumulation volume.
2. A mistake in the use of unsuitable water saturation model(s) has a larger impact on the water saturation estimates for high resistivity hydrocarbon-bearing rocks (R_t > 10 Ohm-m) than on lower resistivity rocks (R_t < 5 Ohm-m). This is caused by the increasing discrepancy between the models' performance with the increase of rock resistivity.
3. The use of the additional models further strengthens the pressumptions that different water saturation models are likely to provide different water saturation estimates.
4. Although various factors are known to have the potential to cause bias in the estimation of water saturation, choice of water saturation model apparentlt plays an important role.
5. Assuming error in water saturation values of 20% from a study in the past, large errors in hydrocarbon reserves estimation – as high as 50% - may occur. However, the errors could potentially be higher considering the higher disparities in the water saturation estimates shown by the different water saturation models used in this study.
6. Well log analysts have to understand well about the water saturation models being used. The understanding should cover aspects related to the models' derivation and their tendency and performance in producing water saturation estimates.
7. Well log analysts have to use all available relevant data in order to maximize credibility of the estimates regardless at what stage of development a field of concern is under.
8. It is an utmost necessity to avoid stand-alone well log interpretations no matter how sophisticated the water saturation model(s) being used.

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