
Converting detail reservoir simulation models into effective reservoir management tools using SRMs; case study – three green fields in Saudi Arabia

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Abstract: Reservoir management requires tools that can provide assessment of the field operation, at high speed and accuracy. Informed decision making requires comparison of a large number of scenarios, considering the uncertainties and risks, in a short period of time. To accomplish reservoir management tasks one must sacrifice either the accuracy or the speed. Numerical models provide accuracy but not at reasonable speed. Analytical techniques provide fast responses but fail to provide accuracy. Surrogate reservoir model (SRM) is developed to address this short coming in reservoir management. SRM replicates the functionalities of numerical model with high accuracy while running at fractions of a second. SRM is trained to learn the principles of fluid flow through porous media as applied to the complexities of the given reservoir, from the simulation model. Application of SRM to three green fields, with multi-million cells models, in Saudi Arabia is demonstrated in this manuscript. [Received: December 23, 2012; Accepted: April 30, 2013]

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1 Introduction

Reservoir management has been defined as use of financial, technological, and human resources, to minimise capital investments and operating expenses and to maximise economic recovery of oil and gas from a reservoir. The purpose of reservoir management is to control operations in order to obtain the maximum possible economic recovery from a reservoir on the basis of facts, information, and knowledge (Thakur, 1996). Historically, tools that have been successfully and effectively used in reservoir management include integration of geology, petrophysics, geophysics and petroleum engineering throughout the life cycle of a hydrocarbon asset. Through the use of technologies such as remote sensors and simulation modelling, reservoir management can improve production rates and increase the total amount of oil and gas recovered from a field.

Reservoir simulation and modelling has proven to be one of the most effective instruments that can integrate data and expertise from a wide range of disciplines such as geology, petrophysics, geophysics, reservoir and production engineering in order to model fluid flow in the reservoir. The reservoir simulation model is history matched using the pressure and production measurements from the asset in order to tune the geological understandings and provide predictive capabilities. Since no two hydrocarbon reservoirs are the same and each asset has its own unique geological characteristics and drive mechanisms, the art and science of reservoir simulation and modelling must be adapted to unique situations in order to be able to realistically model the past and predict the future of a field.

Although reservoir simulation and modelling remains one of the major contributors to reservoir management practices for the foreseeable future (Satter, 1990; Wiggins and Startzman, 1990; Thakur, 1996), its realistic application to reservoir management practices continues to face challenges. These challenges are related to exploration of the solution space that is a natural and required step during a reservoir management study. During reservoir management process it is required to generate, evaluate and rank multiple potential development scenarios as early as possible in the workflow. Furthermore, important practices such as quantification and analysis of uncertainties as well as economic analysis and planning require large number of scenarios to be generated and evaluated in order to assist the decision making process. Performing reservoir management studies without such capabilities reduces the informed decision making to guess work.

This article is organised as follows: upon completion of the introduction (this section) this article continues in Section 2 by examining the requirements of a reservoir management programme addressing some of the issues mentioned in the references mentioned in the previous paragraph. Section 3 presents characteristics of surrogate reservoir models (SRMs) is presented. In Section, 4 criteria for judging the accuracy of a SRM is reviewed. Sections 5, 6, and 7 are dedicated to three case studies. The article is completed by presenting the conclusions in Section 8, followed by Acknowledgements and References.

2 Reservoir management requires fast track analytics

Those involved in reservoir management may or may not be enthusiastic about using reservoir simulation models in their decision making process. One of the issues that are often cited for the lack of the enthusiasm is the lengthy process of querying the reservoir simulation models.

It is a well known fact that as the complexity and the size of an asset increase, so does the time it takes to make a single simulation run that represents that asset. For example, many simulation models that are developed for the assets managed by Saudi Aramco include tens of millions of cells. Actually, with the new initiatives that are currently underway reservoir simulation models with hundreds of millions of cells (or billions of cells) will become the norm.

In order to be able to effectively use reservoir simulation models as a reservoir management tools, these models must have far quicker turnaround time, both in terms and development and run-time (computational time required to perform one complete simulation run). In order to put things in perspective, let us imagine a reservoir management study for given asset. This asset has a reservoir simulation model. The asset is geologically complex and includes a large number of wells. Furthermore, let us assume that water injection has been used in the past several years for pressure maintenance as well as displacement purposes. Moving forward with further reservoir management practices in this asset will require decisions about location and operational constraints of new injection and production wells.

Attempting to address this problem brings up two immediate issues that need to be addressed. First issue is exploring the solution space. For the assumed example, the solution space is a hyper-dimensional space that includes infinite number of possible combinations of producer and injector wells along with an endless possibility of operational constraints (solutions). In other words, there are a large number of possible locations (if not an infinite number of locations) for placing the producer and injector wells. Producer wells can be operated at different bottom-hole pressure values and the amount of the injected water in each well (injection schedule) needs to be optimised.

The second is the fact that even for a history matched model; the static (geological) model is full of uncertainties that need to be quantified. The final decisions that are made must be vetted against the uncertainties associated with the static model in order to make sure that P10, P50 and P90 have been comprehensively examined for all possible scenarios.

Addressing these two issues (exploration of the solution space and quantification of uncertainties) in manner that is statistically representative and significant, requires a very large number of simulation runs (sometimes as many as tens of thousands simulation runs). Even if a single simulation run (using large clusters of parallel processors) take only one hour for a run, in a situation that was mentioned in the example above that may require 10,000 simulation runs, can take about 14 months of continuous computer time. It is easy to see how quickly things can get out of hand and become impractical. Table 1 shows examples of the computational time required to perform meaningful reservoir management analysis using reservoir simulation models.

Table 1 Computational time associated with large number of simulation runs

<i>Run time (min.)</i>	<i>No. runs required</i>	<i>Computational time</i>		
		<i>Hrs.</i>	<i>Days</i>	<i>Months</i>
10	100,000	16,666.7	694.4	22.9
10	50,000	8,333.3	347.2	11.5
10	10,000	1,666.7	69.4	2.3
10	1,000	166.7	6.9	0.2
10	100	16.7	0.7	0.0
30	100,000	50,000.0	2,083.3	68.8
30	50,000	25,000.0	1,041.7	34.4
30	10,000	5,000.0	208.3	6.9
30	1,000	500.0	20.8	0.7
30	100	50.0	2.1	0.1
60	100,000	100,000.0	4,166.7	137.5
60	50,000	50,000.0	2,083.3	68.8
60	10,000	10,000.0	416.7	13.8
60	1,000	1,000.0	41.7	1.4
60	100	100.0	4.2	0.1
300	100,000	500,000.0	20,833.3	687.6
300	50,000	250,000.0	10,416.7	343.8
300	10,000	50,000.0	2,083.3	68.8
300	1,000	5,000.0	208.3	6.9
300	100	500.0	20.8	0.7

Note: Above table does not include the time required for analysis of the results of these runs.

The alternative is to cut corners, rely on expert advice without thoroughly examining the consequences of decisions or to rely on simpler, less advance solutions and let all the expertise and hard work that has gone into developing a sophisticated and representative reservoir simulation model to go unused and/or underutilised.

In a recent publication (Mohaghegh et al., 2009) it was demonstrated that reservoir simulation models, developed by expert geoscientists, reservoir engineers and modellers that are equipped with state of the art simulators, often go underutilised, and the return on the simulation and modelling investments remains low. The major reason for this under-utilisation is that it takes a large amount of time to make a single run of these models.

SRM¹ is specifically developed to convert complex and detail reservoir simulation models into useful reservoir management tools. They perform this important task using pattern recognition capabilities of artificial intelligence and data mining (AI&DM). SRM along with top-down model (TDM)² (Mohaghegh et al., 2012c) are among the tools that have been developed for reservoir management studies.

3 Characteristics of SRM

SRMs have been developed to address the long run-time of reservoir simulation models. SRM is an accurate replica of the reservoir simulation model that runs in a very short period of time (fractions of a second) while keeping the integrity of the solution generated by the reservoir simulation model, intact. The philosophy behind the SRM along with some details on how to develop SRM for the three green fields in the Saudi Arabia that are the subject of this article have been previously published (Mohaghegh et al., 2012a, 2012b). In this article the objective is to discuss some of the characteristics of the developed SRM that makes it specifically attractive to asset managers and its applicability to reservoir management studies. SRM has three impressive characteristics that make it attractive as a reservoir management tool.

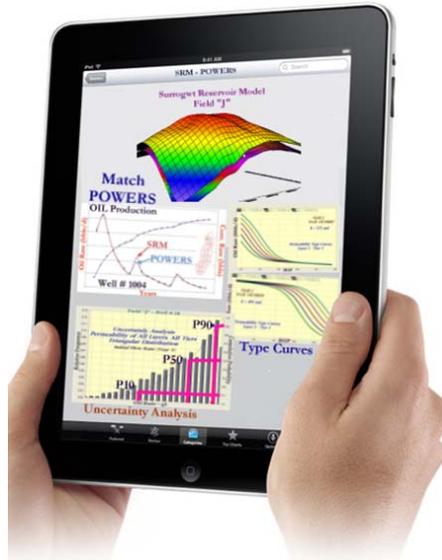
- 1 SRM has small computational footprint. The computational footprint of SRM is so small that it can easily be ported to a PC workstation, a laptop, a tablet or even a smart phone (Figure 1). Once a SRM is trained, calibrated and validated, it is essentially an ensemble of several intelligent agents that are integrated into a single, cohesive module that we have chosen to call 'surrogate reservoir modelTM' or SRM. All parameters that are used in the reservoir simulation models including the geological model at the same resolution that is used in the original dynamic model, and the operational constraints that are imposed (and of course can be changed) are input to the SRM. In other words, there are no differences between how the numerical reservoir simulation model and SRM for a given asset are treated. And since SRM has already been validated with blind simulation runs, reservoir management team can feel comfortable with the high degree of accuracy (when compared to the numerical simulator) that SRM offers.
- 2 SRM runs in fractions of a second. A few SRM runs are equivalent to a complete reservoir simulation run. Well-based³ SRM represents the rate and the pressure of a well (in space and time) in a multi-well asset, taking into account the interaction between wells (interference). Since a single run of a SRM takes only fractions of a second, representation of the entire asset (a complete multi-well, multi-year numerical simulation run) takes only a few seconds.

This small computational time allows for large number of simulation runs (tens of thousands) for a single well, to take only few seconds. Having access to a SRM for an asset can make quantification of uncertainties (using Monte Carlo simulation) associated with the static model a very fast process. Furthermore, a high level manager, will be able to perform very quick development scenarios on the fly (let us say on his/her tablet) and feel comfortable that the results of his/her analyses are not far from the results that could have been achieved by a reservoir modeller spending days and weeks to find out for example how long the production plateau of an asset can be extended if 'x' number of wells are drilled in the next few years.

- 3 SRM is developed using a small number of simulation runs. Although this fact may sound a bit counter-intuitive to those that have been using statistics-based response surfaces, it remains a fact that has been demonstrated over and over, including the three SRM examples that are presented in this article.

A unique and innovative technique that lends itself to the machine learning technology (the technology behind SRM) is used to extract maximum information from a single simulation run. Some details of this technique and a detail demonstration of its applicability were presented in an SPE paper (Mohaghegh et al., 2006).

Figure 1 SRMs have small footprints and are portable (see online version for colours)



Note: SRM can be run on PC workstations, laptops, tablets and smart phones.

4 Accuracy of SRM

To show the accuracy of SRM we demonstrate three recently developed SRMs for green fields in Saudi Arabia. Two of these fields are offshore assets and the third is an onshore asset.

The process of development and validation of the SRMs follows the following path:

- a make nine simulation runs to be used for training, calibration and local validation of the SRM
- b design and run an independent simulation run (this is called the blind simulation run) and generate responses (rate vs. time as a function of certain operational condition – BHP) for all the wells in the asset
- c run the SRM for the blind simulation run and compare the SRM results with the independent simulation (for all wells) as the final validation.

Following is the common theme among the SRMs for the three assets being examined (assets are called offshore fields ‘K’, ‘J’, and onshore field ‘R’): the range of operational constraints (flowing bottom-hole pressures and maximum production rates) for the wells in each of the assets was determined. For each of the assets ten simulation runs were

designed and executed. Nine of the simulation runs were used to train, calibrate and locally validate the SRM. The tenth simulation run was designated as a complete blind simulation run and as a final validation of the SRM. Typical fluid and static properties of these assets are presented in Table 2.

Table 2 Typical properties applicable to all three assets

<i>Fluid property</i>	<i>Top layer</i>	<i>Middle layer</i>	<i>Bottom layer</i>
Reservoir temperature (degrees F)	173	177	182
Bubble point pressure, P_b (psi)	220	174	245
Initial solution GOR, R_{si} (scf/stb)	55	27	41
Formation volume factor at P_b	1.087	1.073	1.077
Oil compressibility (1/psi)	6.645×10^{-6}	6.045×10^{-6}	6.045×10^{-6}
Oil viscosity at P_i (cP)	4.9	6.9	8.8
Oil compressibility, above P_b (1/psi)	11.616×10^{-5}	11.598×10^{-5}	12.079×10^{-5}
API gravity	25.4	23.9	21.8
<i>Ranges of static property</i>	<i>Top layer</i>	<i>Middle layer</i>	<i>Bottom layer</i>
Minimum porosity (fraction)	0.01	0.01	0.01
Maximum porosity (fraction)	0.3	0.3	0.3
Minimum permeability (md)	0.1	0.1	0.1
Maximum permeability (md)	1,000	1,000	1,000

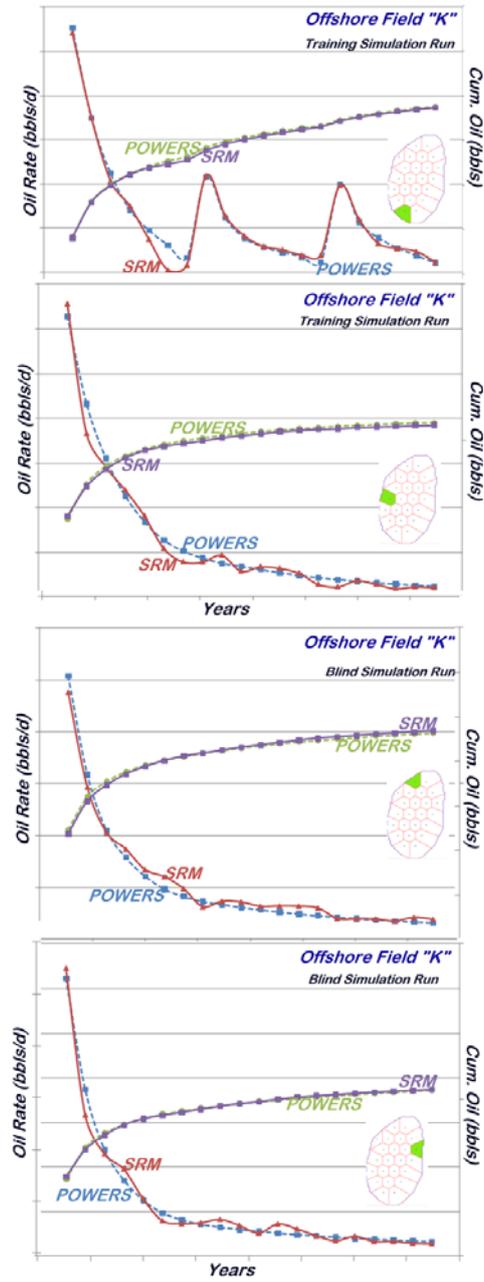
During the development of the SRM (training, calibration and local validation), the geological model and the results of the simulation runs that included oil, water and gas production rates as a function of time, from the nine simulation runs were used for the assimilate a spatio-temporal database that forms the backbone of the SRM. Details on the development of the spatio-temporal database and its use during the development of the SRM have been extensively covered in the previous publications.

5 Offshore field ‘K’

Static model and the results from the nine simulation runs are used to develop a representative spatio-temporal database that is used as the foundation of the SRM. The spatio-temporal database is then used to train, calibrate and locally validate the SRM. During the training and calibration process, the SRM learns the intricate details of fluid flow characteristics in this reservoir. Upon completion of the training process the SRM is capable of understanding the functionalities of the simulation model for this particular asset and is capable of generalising the simulation model’s behaviour. Furthermore, upon completion of the training and calibration of the SRM, it can accurately replicate the results of the numerical simulation model. The generalisation capabilities of the SRM are validated through the use of a new and completely blind simulation run (the tenth run).

Accuracy of the developed SRM in replicating the results of the numerical simulation model is demonstrated in Figure 2. This figure includes four graphs. In each of the graphs four lines are plotted that compare the results of numerical reservoir simulation with SRM. The plots are daily and cumulative well rates versus time.

Figure 2 SRM reproduction of POWERS™ simulation runs results for the offshore field 'K' (see online version for colours)

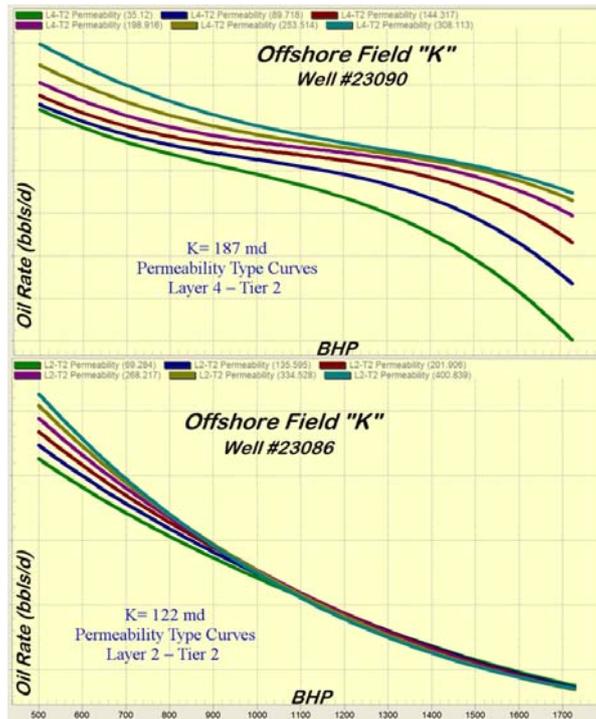


Note: Top two graphs are examples of the training simulation runs and the bottom two graphs are examples of the blind simulation runs.

The two graphs on the top show the reservoir simulation results (Powers™) as well as SRM’s replication of the results for oil flow rate and cumulative oil production versus time for two randomly selected wells representing two of the nine training simulation runs. These figures clearly demonstrate the accuracy of the SRM, noting that the results shown in this figure for each of the wells were generated in fractions of a second by the SRM. The two graphs on the bottom of this figure demonstrate the accuracy of the SRM as it reproduces results for oil flow rate and cumulative oil production versus time for two randomly selected wells representing the blind simulation run.

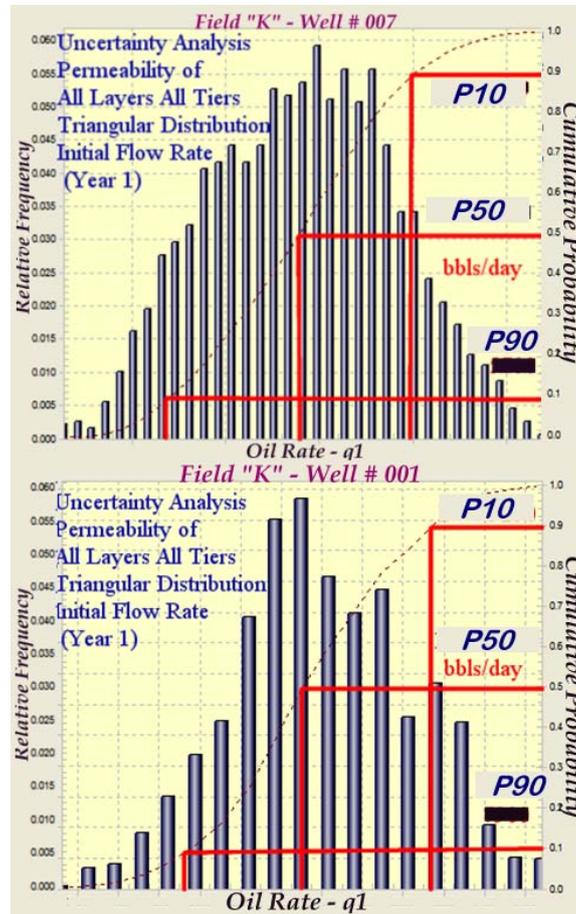
The trained and validated SRM can play an important role as a reservoir management tool. Figures 3 and 4 show examples of use of SRM as a reservoir management tool. In these figures results of thousands of SRM runs are arranged to generate useful plots and information for reservoir management decision making. Figure 3 shows the sensitivity of the reservoir simulation model to reservoir characteristics throughout the asset in the form of type curves. Figure 4 shows how the uncertainties associated with multiple parameters, for example reservoir characteristics, can be quantified using the SRM in conjunction with Monte Carlo simulation.

Figure 3 Type curves generated from the SRM for individual wells in the offshore field ‘K’ (see online version for colours)



Note: These type curves show the sensitivity of oil production to reservoir characteristics at specific locations in the field.

Figure 4 Histograms generated using Monte Carlo simulation applied on the SRM for the oil production from individual wells in the offshore field 'K' (see online version for colours)



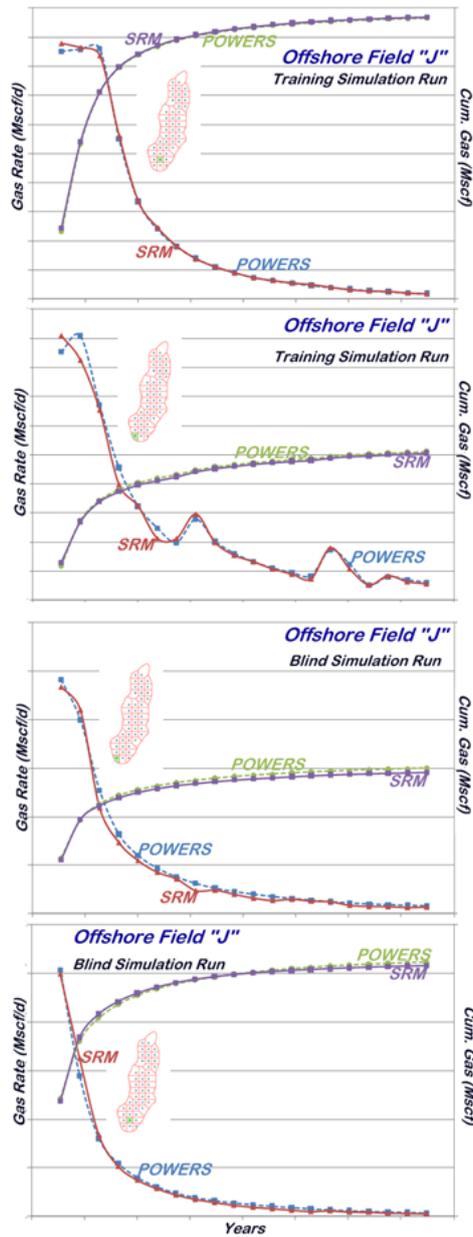
Note: Monte Carlo simulation can quantify uncertainties.

The type curves in Figure 3 are examples of how first year oil production changes as a function of flowing bottom-hole pressure as the permeability slightly away from the wellbore changes in layers 2 and 4 in the reservoir. Each of the graphs in Figure 3 corresponds to a particular well representing a specific location in the field. The drastic difference in production behaviour of these two wells points to the complexity of this reservoir that is compounded by different operational constraints imposed on the offset wells and their impact on the production from the well being studied.

To generate the plot in Figure 4 permeability values all around each well were modified within the range of available permeability values in the reservoir using a uniform probability distribution. Then more than a thousand SRM runs were performed, each time calculating the first year oil rate from each of the wells and plotted. The thousands of the SRM runs were completed in few seconds. The analysis generated the P10, P50 and P90 of oil production under certain operational constraints at any given

location in the reservoir. This can prove to be an indispensable tool for decision making regarding the location of infill wells.

Figure 5 SRM reproduction of POWERS™ simulation runs results for the offshore field 'J' (see online version for colours)



Note: Top two graphs are examples of the training simulation runs and the bottom two graphs are examples of the blind simulation runs.

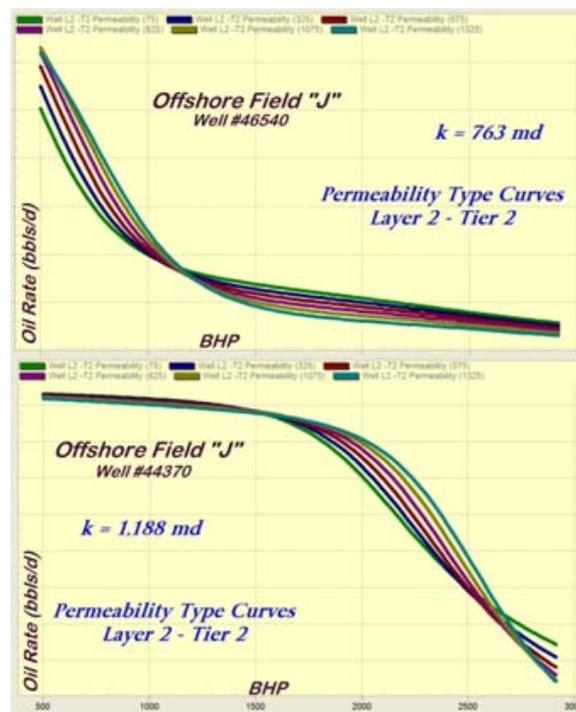
6 Offshore field 'J'

Figure 5 includes four graphs representing offshore field 'J'. The two graphs on the top show the reservoir simulation results (Powers™) as well as SRM's replication of the results for gas flow rate and cumulative gas production versus time for two randomly selected wells representing two of the nine training simulation runs.

These figures clearly demonstrate the accuracy of the filed 'J' SRM, noting that the results shown in this figure for each of the wells were generated in fractions of a second by the SRM. The two graphs on the bottom of this figure demonstrate the accuracy of the SRM as it reproduces results for oil flow rate and cumulative oil production versus time for two randomly selected wells representing the blind simulation run.

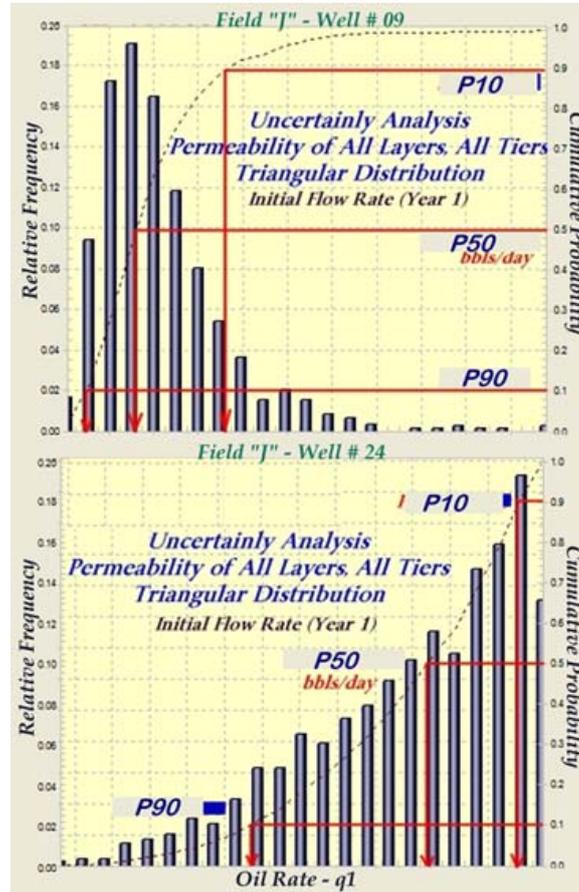
The trained and validated SRM can be used to generate results in practically seconds that can be used as a reservoir management tool. Figures 6 and 7 are examples of use of SRM in such a context. In these figures (similar to those in Figures 3 and 4) results of thousands of SRM runs are arranged to generate useful plots and information for reservoir management decision making.

Figure 6 Type curves generated from the SRM for individual wells in the offshore field 'J' (see online version for colours)



Notes: These type curves show the sensitivity of oil production to reservoir characteristics at specific locations in the field. This information can be used effectively to guide the history matching efforts for each well.

Figure 7 Histograms generated using Monte Carlo simulation applied on the SRM for the oil production from individual wells in the offshore field ‘J’ (see online version for colours)



Note: Monte Carlo simulation can quantify uncertainties associated with any set of reservoir characteristics, identifying indicators such as P10, P50 and P90.

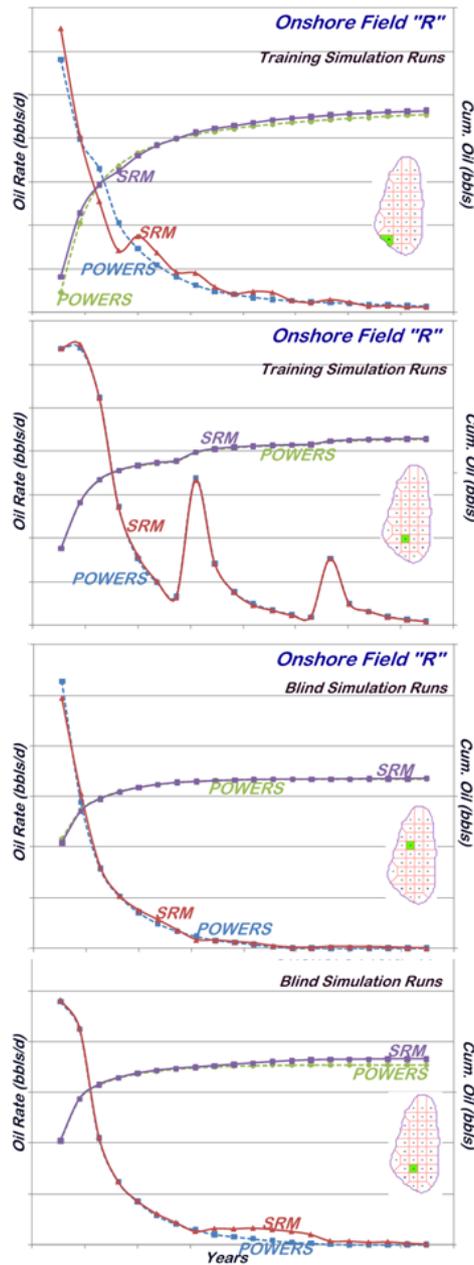
Figure 6 shows the sensitivity of the reservoir simulation model of field ‘J’ to reservoir characteristics throughout the asset in the form of type curves. Figure 7 shows how the uncertainties associated with multiple parameters in field ‘J’, for example reservoir characteristics, can be quantified using the SRM in conjunction with Monte Carlo simulation, where thousands of the SRM runs that are completed in few seconds can display the P10, P50 and P90 of oil production under certain operational constraints at any given location in the reservoir.

7 Onshore field ‘R’

Figure 8 includes four graphs representing the onshore field ‘R’. The two graphs on the top show the reservoir simulation results (Powers™) as well as SRM’s replication of the results for oil flow rate and cumulative oil production versus time for two randomly

selected wells representing two of the nine training simulation runs. These figures clearly demonstrate the accuracy of the SRM, noting that the results shown in this figure for each of the wells were generated in fractions of a second by the SRM.

Figure 8 SRM reproduction of Powers™ simulation runs results for the onshore field ‘R’ (see online version for colours)

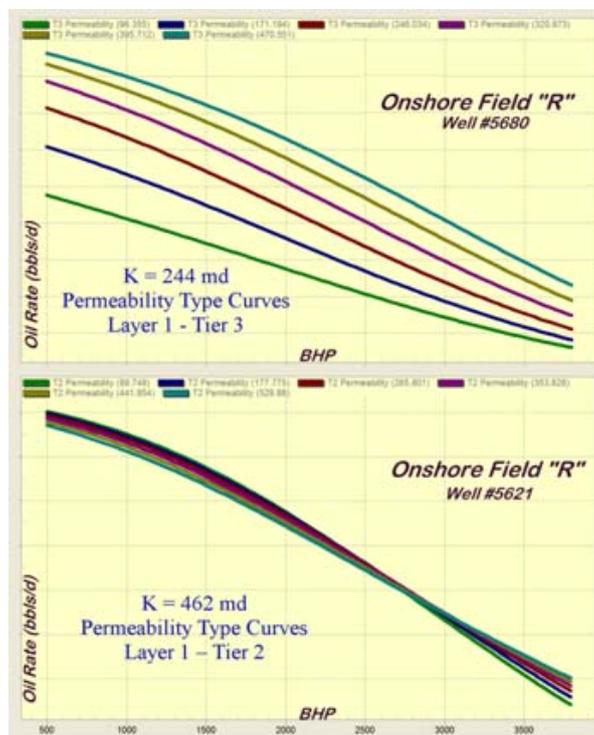


Note: Top two graphs are examples of the training simulation runs and the bottom two graphs are examples of the blind simulation runs.

The two graphs on the bottom of this figure demonstrate the accuracy of the SRM as it reproduces results for oil flow rate and cumulative oil production versus time for two randomly selected wells representing the blind simulation run.

The trained and validated SRM can play an important role as a reservoir management tool. Figures 9 and 10 are examples of use of SRM as a reservoir management tool. In these figures results of thousands of SRM runs are arranged to generate useful plots and information for reservoir management decision making. Figure 9 shows the sensitivity of the reservoir simulation model of field 'R' to reservoir characteristics throughout the asset in the form of type curves.

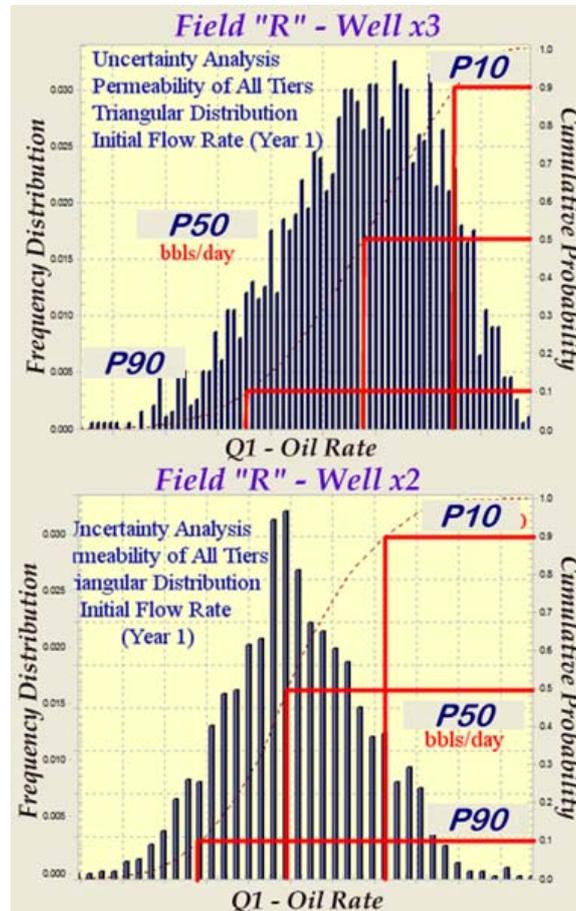
Figure 9 Type curves generated from the SRM for individual wells in the onshore field 'R' (see online version for colours)



Notes: These type curves show the sensitivity of oil production to reservoir characteristics at specific locations in the field. This information can be used effectively to guide the history matching efforts for each well.

Figure 10 shows how the uncertainties associated with multiple parameters in field 'R', for example reservoir characteristics, can be quantified using the SRM in conjunction with Monte Carlo simulation, where thousands of the SRM runs that are completed in few seconds can point out the P10, P50 and P90 of oil production under certain operational constraints at any given location in the reservoir. This can prove to be an indispensable tool for decision making regarding the location of infill wells.

Figure 10 Histograms generated using Monte Carlo simulation applied on the SRM for the oil production from individual wells in the onshore field 'R' (see online version for colours)



Note: Monte Carlo simulation can quantify uncertainties associated with any set of reservoir characteristics, identifying indicators such as P10, P50 and P90.

8 Conclusions

SRM is an accurate replica of complex, numerical reservoir simulation models that can run in fractions of a second. SRM can reproduce results that are within 90% to 99% of the results from the reservoir simulation models.

Furthermore, thanks to a unique and innovative data assimilation and compilation technology, SRM can achieve this level of accuracy using a small number of reservoir simulation runs. The developed SRM has a small computational footprint and can be ported on PC workstations, laptops and even tablets and smart phones. SRM increase the return on reservoir simulation and modelling investment by making them accessible to a variety of reservoir management tasks.

Results of SRM development for three green fields in the Saudi Arabia were presented and their potential use as a reservoir management tool was demonstrated.

Acknowledgements

This is a new and original technical paper. However, materials from two SPE papers, both of which have been referenced here, have been used extensively in compiling this manuscript. The author would like to acknowledge and thank colleagues and co-authors in the original two papers from Saudi Aramco (Jim Liu and Olugbenga A. Olukoko) and Intelligent Solutions, Inc. (Razi Gaskari and Mohammad Maysami) for their contributions to this study.

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Notes

- 1 SRMs are invented and introduced to the industry in 2005 by Intelligent Solutions, Inc.
- 2 Top-down models (TDMs) are invented and introduced to the industry in 2010 by Intelligent Solutions, Inc.
- 3 Well-based SRM are emphasised here to distinguish it from another type of SRM called 'grid-based SRM'. Grid-based SRM accurately replicates pressure and saturation changes during a simulation run at the grid block level.