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# Ranking Reservoir Realizations Using SAGD Proxy and Gradual Deformation Method

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*The first step in making a simulation model is generating realizations for different reservoir properties such as porosity, permeability and water saturation. For this reason, geostatistical methods can be used. Ranking realizations for assessing uncertainty and finding P10, P50 and P90 is the next step. There are different ranking measurements. As an example, ranking can be done based on the calculating OOIP, or calculating connected hydrocarbon volume, or considering cumulative oil production or net present value (NPV) after a long period. Between all of these methods, NPV is perhaps the best ranking measure because it considers different factors such as oil and steam production costs, amount of oil and steam production at different time steps and also discount rate. For this reason, each realization should be run with reservoir simulator. Usually running time of reservoir simulator is very large. Especially in simulating SAGD wells, thermal simulator should be used, and running time of thermal model is larger than conventional model with the same number of cells. Due to the project time limitations, it is impossible to run all of realizations with the reservoir simulator. For solving this problem, a SAGD proxy model based on the Butler's theory has been developed. This proxy is much faster than simulator and it can gives estimated oil and steam production rate at different time steps by considering heterogeneity in reservoir models. Results showed high correlation coefficient between ranking results of proxy and reservoir simulator.*

**Introduction**

Simulating reservoir behavior is one of the most important steps in production optimization. For building a simulation model, at first static model should be generated. For this reason Geostatistical methods can be used for simulating different reservoir properties. Most of these methods are based on variogram plotting and kriging for minimizing variance of estimation. Then, Monte Carlo Simulation (MCS) can be used for generating different realizations. The most popular method for MCS is Sequential Gaussian simulation (SGSIM) which is recursive application of Bayes law. Number of simulation realizations should be large enough to ensure adequate sampling of the full space of uncertainty (Ding et al., 1992). Our information about true model only limited to the well locations. Due to the lack of enough information about the true reservoir model, uncertainty in the reservoir parameters should be quantified. Uncertainty in different parameters can lead to the uncertainty in production results after flow simulation. The best method for quantifying this uncertainty is running all models with the flow simulator. Because simulator running time is large, it is very time consuming to run all of them for quantifying uncertainty. For this reason, number of static models should be reduced while still they are representative of uncertainty in the reservoir. This can be done by ranking realizations. Ranking can reduce multivariate distribution of facies, porosity, permeability and water saturation to a scalar. Ranked realizations can be divided into different groups and then one realization from each group can represent uncertainty of that group. Most of the time, realizations classified into three different groups for identifying the low (P10), medium (P50) and high (P90) realizations. Then, these realizations can be used for flow simulation. These realizations can effectively characterize production uncertainty. There are different ranking measurements. Some of them are only based on static models and some of them are based on the flow simulation and running reservoir model with flow simulator. Ranking parameter must be highly correlated with production performance of reservoir. The best ranking measurement can be obtained by running flow simulator for finding production rates, but as we mentioned before, due to the large running time it is impossible to run all of realizations with flow simulator. For this reason, simpler methods should be selected for quick ranking of realizations. The best method is the one that gives a high correlation coefficient with real ranking index.

In general, ranking methods can be divided into two different categories: 1- Static methods 2- Dynamic methods.

Static methods can be divided into the following sub-methods: a) Volumetric methods b) Statistical methods c) Global connectivity d) Local connectivity. Volumetric method is based on calculating OOIP and ranking realizations based on this parameter. This method is the simplest method, but usually is not a good measure for ranking and it has low correlation coefficient with real ranking indices. Formula for this method is

$$OOIP = \sum_{z=1}^{n_z} \sum_{y=1}^{n_y} \sum_{x=1}^{n_x} V_{(x,y,z)} (1 - S_{w_{(x,y,z)}}) \phi_{(x,y,z)} . \quad (1)$$

In this equation $V$ is volume, $S_w$ is water saturation and $\phi$ is porosity and $n_x$, $n_y$, and $n_z$ are number of grids in different directions.

Although this equation can be improved by considering only net cells, but still it is not a very good ranking measurement. In the case of considering net cells, formula for computing OOIP is:

$$OOIP_{Net} = C \sum_{z=1}^{n_z} \sum_{y=1}^{n_y} \sum_{x=1}^{n_x} V_{(x,y,z)} (1 - S_{w_{(x,y,z)}}) \phi_{(x,y,z)} \, i_{(x,y,z)} \quad (2)$$

In this equation, $i$ is a categorical variable and its value is 0 if cell has porosity or permeability less than the cutoff value, otherwise it is equal to 1.

Statistical methods are based on computing average of porosity, permeability and water saturation or based on net sand proportion or non-net shale proportion.

In SAGD process, amount of oil production depends on connection of steam chamber to surrounding reservoir. This connectivity can be divided to global and local connectivity. Global connectivity indicates proportion of net reservoir connected within drainage volume. A cell is connected globally when it is net (porosity and permeability is greater than cutoff, $i_{net} = 1$) and connected to one or more neighboring net cells ($i_{GC} = 1$). Global connectivity is a good ranking measurement in homogeneous reservoirs. As a result, fraction of globally connected cells can be defined as:

$$F_{GC} = \frac{\sum_{z=1}^{n_z} \sum_{y=1}^{n_y} \sum_{x=1}^{n_x} i_{net\,(x,y,z)} i_{GC\,(x,y,z)}}{V} \quad (3)$$

Local connectivity depends on ability of steam chamber to reach and recover bitumen within local windows. Usually global connectivity is not the same as local connectivity. In SAGD process, steam can spread in a certain window, not all parts of the reservoir. Global connectivity will consider all parts of the reservoir, but local connectivity can consider a window around producer and injector wells. Global connectivity can be very large, but local connectivity can be much smaller. In this case, formula for calculating local connectivity is:

$$F_{LC} = \frac{\sum_{z=1}^{n_z} \sum_{y=1}^{n_y} \sum_{x=1}^{n_x} i_{net\,(x,y,z)} i_{LC\,(x,y,z)}}{V} \quad (4)$$

McLennan el al. (2005) used these methods for ranking realizations. They ranked realizations from McMurray formation based on the cells connectivity and then calibrated results using flow simulator results. They showed reliable results can be found using these methods.

Similar to the local connectivity, connected hydrocarbon volume (CHV) can be calculated based on the following formula:

$$CHV = \sum_{y=1}^{n_y} \sum_{x=1}^{n_x} i_{net\,(x,y)} \, (1 - S_{w_{(x,y)}}) \phi_{(x,y)} \quad (5)$$

In this formula, $i_{net}$ is an indicator of connectivity defined as 1 if cell is connected to the well and as 0 otherwise. This can be done on different $xy$ slices and then sum over all slices. Again a window should be defined around wells. Also connectivity calculation must be modified in two ways: 1- limit within a maximum distance from the well 2- Consider connected cells to production well as connected. Also a direct line of sight to the production well can be considered. Then all of net cells along these lines can be considered for calculating connected hydrocarbon volume. Fig. 1 shows considering connected cells along line of sight and in a window around production well. All connected cells outside of window should be ignored. Fenik et. al. (2009) used this method for ranking realizations. They compared connected hydrocarbon volumes for different models with different simulator outputs and found a good correlation between CHV and simulator results.

Also dynamic methods are related to running the reservoir simulator. In these methods, user may simplify flow equations for faster simulation. This simplification may reduce ranking correlation with real production data in some of methods, but still correlation coefficient can be higher than volumetric or statistical or connectivity methods. Examples of these methods are random-walk, time-of-flight (TOF), tracer, streamline setups and proxy.

The most accurate ranking method is based on the running full model with simulator for calculating cumulative oil production, cumulative water production and NPV. Usually dynamic methods are slower than static methods. Formula for NPV is:

$$NPV = \sum_{i=1}^{N_t} \frac{\nu_o Q_{oi} - \nu_w Q_{wi}}{(1+r)^{t_i}} \tag{6}$$

In this formula, $i$ is time step index, $N_t$ is total number of time steps, $r$ is discount rate, $t_i$ is cumulative time since start of production, $\nu_o$ and $\nu_w$ are price of oil and cost of steam production, $Q_{oi}$ and $Q_{wi}$ are total oil and steam production over the time step $\Delta t_i$. Using this formula, all of important factors can be considered. Discount rate can be set to zero or set as 10% per year. If it is not zero, it can add more weight to early production period. Fig. 2 shows two different cases. Although case 1 has less cumulative oil production at the end of 15 years production, but due to the higher production at the early time steps, with discount rate of 10% it has higher NPV than case 2.

Zanon et. al. (2005), created a full analytically space of uncertainty and showed how ranking can helps to sample more efficiently than MCS. They used Kolmogorov-Smirnov test for measuring closeness of ranked realizations and MCS. They ranked realizations based on the NPV.

Vanegas et. al. (2009) used a proxy based on the Butler's SAGD theory for ranking realizations. They considered a synthetic 3D well pad with 8 well pairs as a case study. They ranked realizations based on the cumulative oil production, but they didn't compare results with reservoir simulator and just show the uncertainty of realizations after ranking by proxy.

In this paper, we developed a proxy based on the Butler's SAGD theory and realizations are ranked based on the actual ranking index which is NPV. In this theory, only location of producer can be considered. Location of injector is 5-10 meters above producer. Location of producer is close to the bottom of the reservoir and its trajectory can be optimized after finding a reliable proxy. In this theory, steam chambers grow to the top of the reservoir and then spread sideways. Using this theory (Butler 1987; Butler 2000), location of interface, rate of heat penetration and also oil production from different segments of interface can be found. Also Rose (1993) developed an equation for estimating steam oil ratio for Butler's proxy. In 2008, Jose Walter Vanegas added different options to this proxy for considering heterogeneity and also adjusting different parameters (Vanegas and Deutsch, 2008).

In this work, different options have been added to the proxy for making it possible to predict oil and steam productions of realistic models. These options are:

1- Considering wells with non-horizontal trajectory.
2- Using different number of facies and considering one relative permeability table for each facies and also calculating relative permeability in a more efficient way.
3- Using different PVT regions and as a result different PVT tables.
4- Using different rock thermal properties. Thermal rock types can be found from shale volume in each grid.
5- Effect of pinchout, gas zone and water zone can be considered in this proxy. Pinchout has very low permeability and they are important in optimization. Also gas and water zones have significantly higher conductivity than oil zone and they cause increasing heat lost to the overburden. This effect should be considered; otherwise matching CSOR would be very difficult or even impossible.
6- Adjusting spreading rate of steam chamber is very important. If this rate is very fast, interface moves very fast and reaches to the boundary in early time steps. In this case, matching proxy results with simulator is very difficult. Also if this rate is very slow, front moves slowly and cannot produce much of the oil in that place.

7- For adjusting parameters, a robust optimization algorithm is critical. Without having a good optimization algorithm finding a good fitting is very difficult. Simulated annealing is a slow method and its efficiency is not very good. We added 3 different optimization algorithms to the code and user can select which one is better for adjusting. These algorithms are 1- Sequential quadratic programming (SQP) 2- Differential evolution 3- Particle swarm. Using these algorithms, different parameters can be modified for finding a good match between results of proxy and simulator.

**Case study**

In this paper, a case study has been considered. For this reason, 100 realizations from a real 3D model have been generated. This is a pretty complicated case with a bottom pinchout and top water and top gas. Two facies with 7 different thermal rock types existed in this model. Well is along $\mathrm{x}$ direction. Grid dimensions are $26 \times 32 \times 83$. Grid size in $\mathrm{x}$, $\mathrm{y}$ and $\mathrm{z}$ directions are 25 $\mathrm{m}$, 2.5 $\mathrm{m}$ and 1 $m$ respectively. Also 21 PVT regions existed in this reservoir. The following procedure has been used for Geostatistical modeling of these realizations.

First of all, horizontal and vertical variograms using all of the data have been plotted for different properties. Then two vertical wells have been drilled in the model for sampling data. Because there is a clear trend in the data, $3D$ trend model has been modeled. Then different facies have been modeled by sequential indicator simulation using $3D$ trend model. BLOCKSIS software has been used for this reason. Fig. 3 shows one slice of one of the generated realizations in $xz$ and $yz$ directions after importing to the simulation model.

As you can see in Fig. 3, there is low permeable formation above the sand formation which mostly contains water. Also at the top of the reservoir, some of layers are gas bearing layers.

Then, porosity modeled by-facies and then results of different facies have been merged together based on the facies map.

Then permeability realizations have been generated using bi-modeling method. Fig. 4 shows one slice of one of the generated permeability realizations in $xz$ and $yz$ directions after importing to the simulation model.

Finally, water saturation realizations have been generated using co-located co-kriging with porosity realizations.

Using above procedure, 100 realizations have been generated. There is uncertainty between different properties in different realization. This uncertainty can cause different cumulative oil and cumulative steam production during SAGD process after running these models with flow simulator. As we talked later, due to the large running time, running all of the models by flow simulator is very time consuming. For this example, simulator running time for running each realization is about 10 hours. For this reason, CMG (Computer modeling group) simulator and STARS software can be used for thermal simulation of different realizations. For quantifying uncertainty and selecting limited number of realizations that represent this uncertainty, realizations should be ranked. For this reason we developed a SAGD proxy model which has different applications. One of them is ranking realizations by running proxy instead of reservoir simulator. As we talked before, this proxy is based on Butler's SAGD model. This proxy is very fast and running each realization using this proxy takes about one minute compare to 10 hours by simulator. For assessing ranking efficiency, results of different methods can be compared with each other. In this work, at first we run all of realizations with flow simulator. Then we calculated 3 different measurements for each realization 1- Cumulative oil production 2- NPV with 10% discount rate and 3- NPV with zero discount rate. Then realizations have been ranked based on each of these factors and results compared with three other ranking methods: 1- Volumetric ranking by calculating OOIP 2- Connected hydrocarbon volume by considering local connectivity 3- Proxy ranking. Similar to the simulator, proxy measured three different factors: 1- Cumulative oil production 2- NPV with 10% discount rate and 3- NPV with zero discount rate. Other methods are unable to consider effect of oil and water prices, discount rate and amount of oil and steam productions. There are limited numbers of parameters in the proxy that can be calibrated for finding better results. These factors are adjusting factor for rising period, adjusting factor for spreading period, adjusting factor for averaging permeability, adjusting factor for CSOR and adjusting factor for steam chamber pressure. This calibration can be done by modifying these values for finding a good match between proxy results with one of simulator runs. For matching oil and steam production rates, different optimization algorithms can be used for minimizing mismatch. As an example, sequential quadratic programming, which is a very efficient constrained optimization algorithm, can be used for calibrating proxy. In this paper, results of both uncalibrated and calibrated proxy will be considered.

NPV can be obtained from Eq. 6. For this case oil price is $500/m$^3$, steam production cost is $30/m$^3$ and discount rate is 10% per year. Based on these values and also oil and steam production at different time steps, NPV can be obtained for both of proxy and simulator. After that all of realizations can be ranked based on the NPV. It is desirable to find a quick method which gives a high correlation coefficient with the NPV ranked results of simulator. Fig. 5 shows comparison between simulator NPV and proxy NPV (for both uncalibrated and calibrated cases) , OOIP and also CHV (connected hydrocarbon volume). In this figure, higher ranking index means lower NPV or other properties.

As you can see in Fig. 5, correlation coefficient between simulator NPV results and Proxy NPV results are higher than other methods. Difference between results of uncalibrated and calibrated proxy is not significant and calibration has been done only by modifying CSOR factor. In this case, results of OOIP and CHV are very close to each other and they have correlation coefficient significantly smaller than proxy. A new version of CHV software is developing and that software probably can gives higher correlation coefficient.

Although in this case calibration did not help too much, but calibration has different applications. As an example, it can be used for prediction period or optimization by changing well path. In this case, after calibrating results, there is no need to run reservoir simulator and instead of running simulator, proxy can be called for finding approximate oil and steam rates. Another application of calibrated proxy is related to estimating oil and steam uncertainty for realizations. For estimating uncertainty instead of running all of realizations with simulator, calibrated proxy can be used for quick and reliable estimation of cummulative oil and steam rates for all 100 realizations. Fig. 6 shows comparison between simulator and proxy resuls. In Fig. 6 the bounds of each box are 25% and 75% quantiles, the whiskers are the extremes, the line in the box is the median median, and the crosses shows the outliers. An outlier is any value that lies more than 1.5 times the interquartile range (IQR) from either end of the box. The IQR, is just the width of the box in the box-and-whisker plot. As a result, each box contains 50% of data . As you can see, proxy estimated range of cummulative oil and cummulative steam productions with pretty good accuracy. Running all of realizations with simulator is very time consuming and fast approximation of uncertainty can be a very useful. Calibrating the proxy has been done only by modifiying CSOR and spreading period adjusting factor and just by comparing the final oil and steam production of simulator and proxy for the first realization. There is no need for finding accurate match between simulator and proxy results. In proxy predictions, although variance of data is more than variance of simulator results, but pretty good accuracy achieved. Medians in both cases are pretty the same.

By comparing simulator oil production with proxy oil production, higher correlation coefficients may be obtained. Adding other factors such as oil and water prices, discount rate and steam production rates, may decrease correlation coefficient. This decreasing in correlation coefficient should be more significant for OOIP and CHV methods, but this decrease for proxy should be less than other methods, because proxy can consider effect of all of these factors, but other methods cannot consider these factors. Fig. 7 shows this comparison only by considering simulator and proxy oil production rates instead of NPV.

In this cas, results of calibrated and uncalibrated proxy are the same due to CSOR calibration which does not have any effect on the cummulative oil production rates. Correlation coefficient for proxy increased a little bit. Also results of CHV and OOIP imoroved too. This improvement for proxy is less than other methods. This can proves the fact that effect of including other factors such as oil and steam costs, discount rate and cummulative water production on the proxy is not significant and proxy can rank realizations based on the NPV or cummulative oil production rates with good accuracy and difference in the final correlation coefficients is not significant.

Large dispersion of points from 45 degree line is not desirable and in the ideal case all of the points should be on or close to this line. But these ranking indices cannot show distribution of ranked realizations. For finding P10, P50 and P90 the interval should be divided into three groups and it is desirable to have a narrow distribution for each of these groups, because it can decrease uncertainty of estimating P10, P50 and P90. For this reason, all of the values such as NPV, CHV values and OOIP can be standardized and then compare with each other. Standardized values can show distribution of values in each group clearly. For standardizing values, the following formula can be used:

$$Y = \frac{Z - \mu}{\sigma} \tag{7}$$

Where $Z$ is value in original unit, $\mu$ is mean and $\sigma$ is standard deviation. This formula gives the standardized value of $Z$ which is $Y$. Fig. 8 shows simulator NPV comparison with other methods based on the standardized values.

As you can see in Fig. 8, dispersion of points from 45 degree line in proxy results are much less than OOIP and CHV methods. As a result, finding P10, P50 and P90 using proxy results would be much closer to the simulator results than other methods. Again results of uncalibrated and calibrated proxy are very close to each other.

In all above cases, discount rate was 10% per year. For long term production, it is better to only consider oil and steam rates and their costs by considering zero discount rate. Except proxy, non of ranking methods can consider effect of discount rate. For this reason, probably this assumption can improve results of other ranking methods, but this effect on proxy should be negligible. Fig. 9 shows effect of zero discount rate on correlation coefficient between simulator NPV and other methods.

As you can see in Fig. 9, correlation coefficient for CHV and OOIP ranking methods increased, but for calibrated and uncalibrated proxy, correlation coefficient didn't change significantly and they increased slightly. As we talked before, this is due to accounting discount rate in the proxy calculations.

Also Fig. 10 shows comparison between cumulative oil production of simulator (red) and proxy (blue) for P10, P50 and P90 realizations. As we expect, there are pretty good matches between P10, P50 and P90 realizations. In this case, due to the existence of top water and top gas, heat loss to the overburden is significant. For this reason, usually amount of steam injection is close to the amount of steam production and difference between cumulative steam productions of different realizations is not significant and P10, P50 and P90 realizations have very close cumulative steam rate. Fig. 11 shows changing steam rates for P10, P50 and P90 realizations. If you look at the changing in the rates for full 15 years, you cannot recognize difference between cumulative steam rates of different realizations. For this reason, in this plot only the last 2 years has been shows for better visualization of differences. In this case study, rate of steam injection is 100 $m^3$/day. As a result, if we assume all of injected steam can be produced due to the large heat loss, final cumulative steam production should be around 547500 $m^3$. Fig. 11 shows final cumulative steam production for different realizations are around this value. But still they have effect on NPV calculation of different realizations and as you can see in Fig. 7 and Fig. 9, results of different methods are slightly different.

Also Table 1 shows Corresponding simulator rank for P10, P50 and P90 of proxy realizations. As you can see difference between P10 and P90 of simulator and proxy are not significant. But P50 of proxy is P34 of simulator realizations. It means that for proxy P50, NPV should be smaller than simulator P50 NPV and actually proxy found P34 instead of P50. As you can see in Fig. 10, still there is a good match between P50 of proxy and P50 of simulator and final cumulative oil production of simulator and proxy are close to each other and difference is not significant. This is due to two reasons: 1-Early production in simulator P50 realization is higher than proxy P50 realization 2-Cummulatove water production for proxy is higher than simulator. As a result, these two factors cause difference between NPV of proxy and simulator be larger than their cumulative oil production differences.

**Gradual deformation method for re-ranking realizations**

Although ranking by proxy can gives correlation coefficient greater than 0.9, but if you look at the ranking cross plots between proxy and simulator, some outliers around the 45 degree line can be found. For example, as you can see in Fig. 5, P5 of proxy is equal to the P36 of simulator. If we want to pick P5 just based on the ranking results of proxy, we may find a realization which is far from the simulator results. Although in this plot correlation coefficient is 0.91, but still there are some outliers in the results. In this case, proxy P4 and P6 are very close to the simulator P4 and P6 and just proxy P5 is far from the simulator P5. We did not have any problem in selecting P10, P50 and P90 realizations and results were close to the simulator results, but these outliers can cause problem in finding range of uncertainty and ranking realizations. Especially if proxy P10, P50 or P90 are one of these outliers, it can make a big problem in ranking the realizations. For this reason, in this paper gradual deformation method which is introduced by Ying et al. (2000) and Hu (2002) has been considered. Probably by using P4 and P6 realizations and combining them with P5, a new realization which is much closer to the simulator P5 can be found. In this method conditional realizations can be combined for generating a new realization which has the same covariance (variogram) as each of single realizations. Consider a case that different dependent normal random functions $Y_i(x)$ should be combined together:

$$Y(x) = \sum_i \alpha_i Y_i(x) \tag{8}$$

$\alpha_i$ are coefficients that should be multiplied with different realizations. They showed that two conditions are necessary for generating a new realizations with the same covariance (variogram) and conditioned to the data. For conditiong to the data the summation of all coefficients should be one:

$$\sum_i \alpha_i = 1 \tag{9}$$

Also for generating the same covariance matrix, summation of square of all of the coefficients should be again one.

$$\sum_i \alpha_i^2 = 1 \tag{10}$$

Assume that two realizations should be combined together. Based on these two conditions, one of the coefficients should be 1 and another should be 0. So, this method works when three or more realizations need to be combined together. In this paper, only combining three realizations has been considered, but combining more realizations by having these two conditions is possible. In case of having three realizations, these three coefficients are the circle of intersection between the plane $\alpha_1 + \alpha_2 + \alpha_3 = 1$ and the sphere $\alpha_1^2 + \alpha_2^2 + \alpha_3^2 = 1$. Ying et al. (2000) showed that these coefficients can be found from the following formula:

$$\begin{gathered} \alpha_1 = \frac{1}{2}\left[1 - \alpha_3 \pm \sqrt{(1-\alpha_3)(1+3\alpha_3)}\right] \\ \alpha_2 = \frac{1}{2}\left[1 - \alpha_3 \mp \sqrt{(1-\alpha_3)(1+3\alpha_3)}\right] \\ \alpha_3 \in [-1/3\,, 1] \end{gathered} \tag{11}$$

Also Hu (2002) proposed the following direct formulas for finding these coefficients:

$$\begin{gathered} \alpha_1 = \frac{1}{3} + \frac{2}{3}\cos t \\ \alpha_2 = \frac{1}{3} + \frac{2}{3}\sin(-\frac{\pi}{6} + t) \\ \alpha_3 = \frac{1}{3} + \frac{2}{3}\sin(-\frac{\pi}{6} - t) \end{gathered} \tag{12}$$

where $t \in [-\pi, \pi]$. A value fot $t$ between this range can be selected randomly and all of these coefficients can be found easily. As a results, by using different seed numbers, different combined realizations can be found easily.

For testing efficient of this method, we tried to combine P4, P5 and P6 proxy realizations in the Fig. 5 to see the combined realization is closer to the P5 simulation realization or not. For this reason, different random seed numbers have been used for checking the sensitivity of method on the results. You can see the results in the Fig. 12. In this figure, yellow curves show cumulative oil production for different combined realizations. Red curve shows simulator P5, and black curves show cumulative oil production for P4, P5 and P6 proxy realizations. As you can see, in all of these cases, combined realizations are close to the simulator P5. In the limiting case, where two of coefficients are zero or close to the zero, combined realization is equal to the third realization. We did not find any combined realization that gives the worse result than the original P5 proxy realization.

Using this idea, we re-ranked all of the realizations by combining every three realization together. For example, P1, P2 and P3 realizations combined together, then P4, P5 and P6 realizations combined together and etc. Then 33 new realizations have been generated from the original 100 realizations. Then all of these 33 new realizations have been ran with the simulator to check the correlation coefficient between the simulator and the new re-ranked proxy realizations. Fig. 13 shows the results of re-ranking. As you can see, correlation coefficient is close to 0.95 and outliers tempered using this method. The new realizations can be used for finding P10, P50 and P90 realizations. For example P3 in the new 33 realizations can shows the P10 of all 100 realizations approximately.

**Conclusion**

This paper shows a quick and reliable method for ranking SAGD realizations. This method is based on Butler's SAGD theory. Using this method, oil and steam production rates can be estimated quickly. The running time for each realization using the proxy is about one minute compared to the 10 hours using simulator. For assessing efficiency of ranking, 100 realizations have been tested by simulation. NPV and cumulative oil production rates have been computed for different realizations and realizations ranked based on these parameters. Then, results of ranking have been compared with different methods such as OOIP, connected hydrocarbon volume and also proxy. Ranking comparisons showed that proxy results have high correlation coefficient with simulator results, which was greater than 0.9. This correlation coefficient is significantly higher than other methods. Also using gradual deformation method, realizations are combined together for removing outliers from the ranking results. The new combined realizations are more reliable and can be used for ranking realizations.

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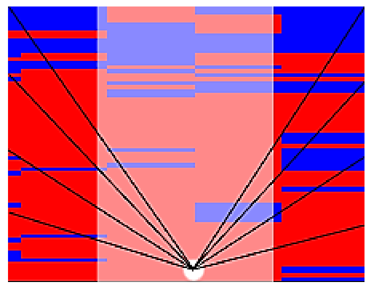


Figure 1: Connected cells along line of sight and in a window around production well

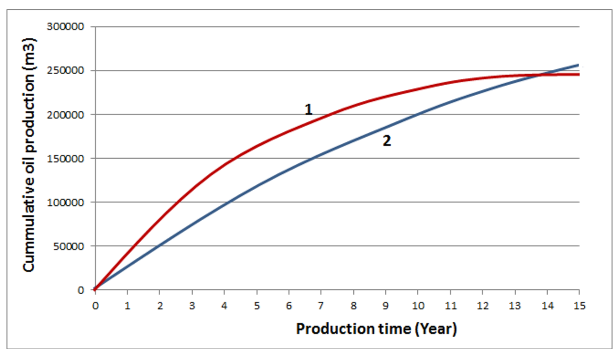
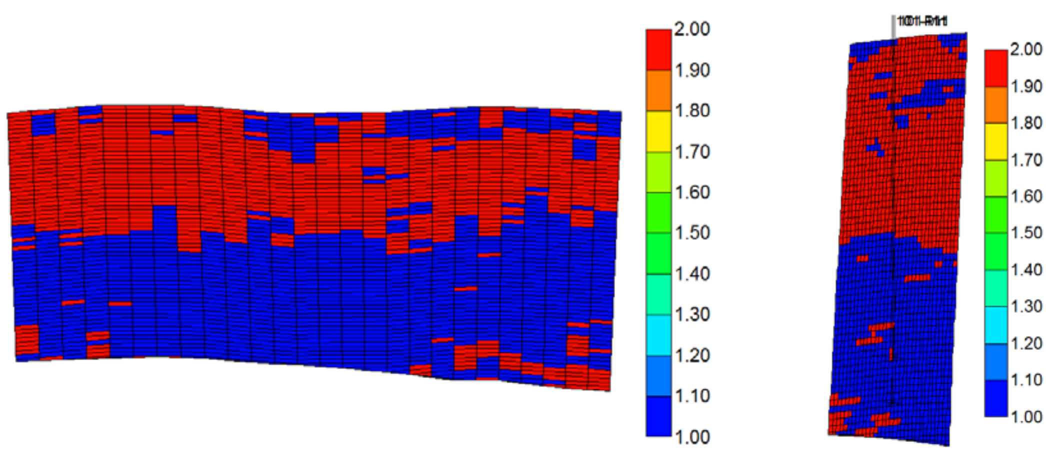
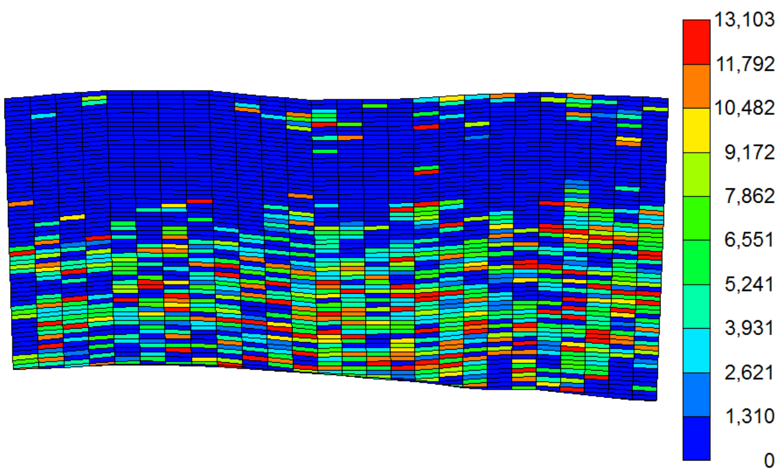


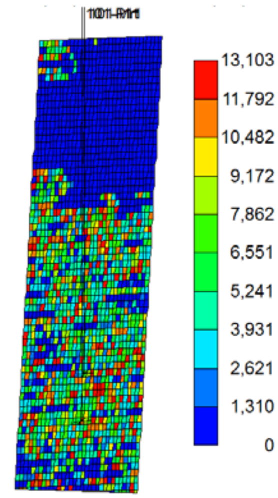

Figure 2: Effect of discount rate on NPV




(a) XZ slice (b) YZ slice

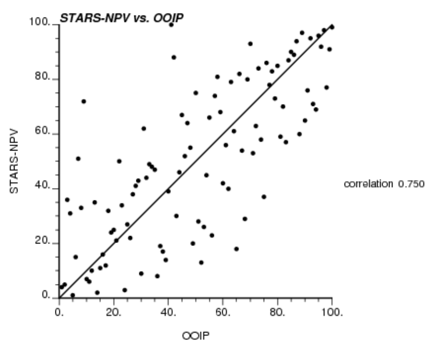
Figure 3: One slice of one of generated facies realizations in different directions



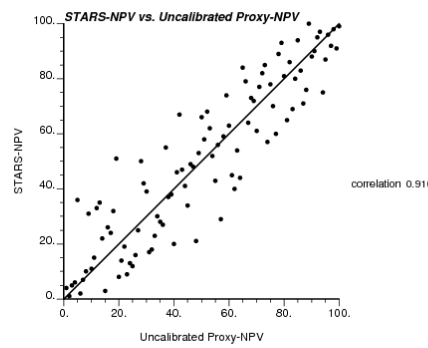




(a) XZ slice (b) YZ slice

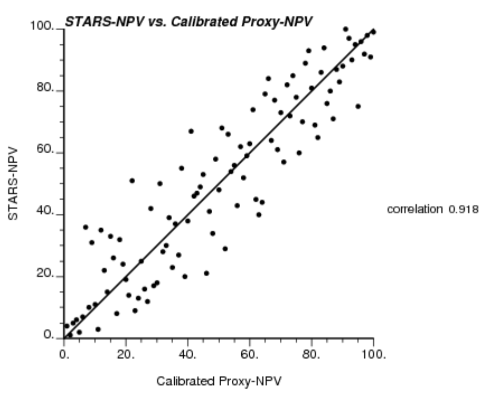
Figure 4: One slice of one of generated permeability realizations in different directions



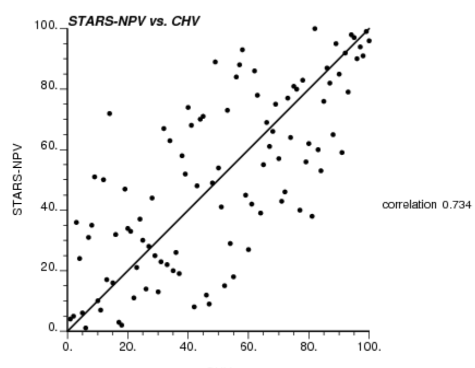

(a) Simulator NPV vs. OOIP




(b) Sim. NPV vs. uncalibrated proxy NPV




(c) Sim. NPV vs. calibrated proxy NPV




(d) Simulator NPV vs. CHV

Figure 5: Correlation coefficient between NPV results of simulator and other methods

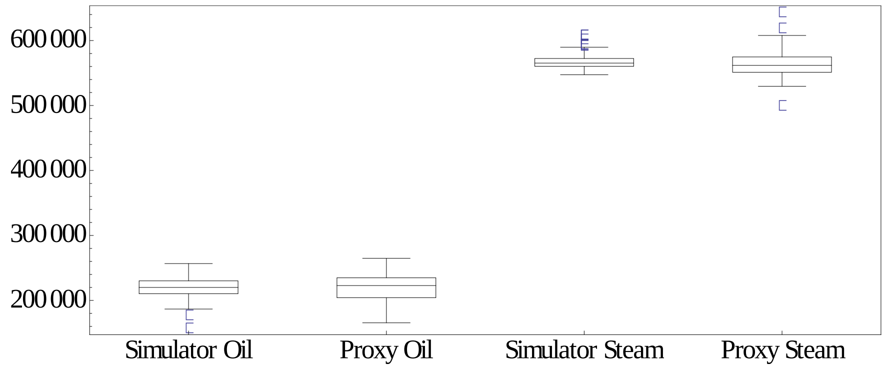
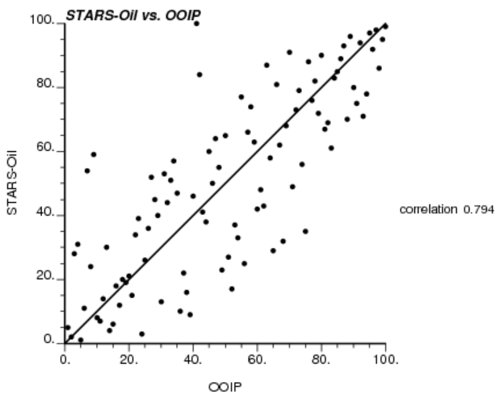
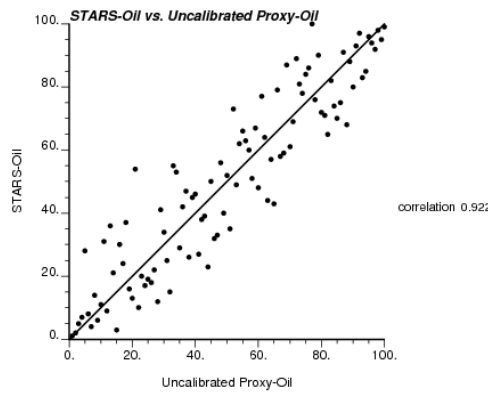


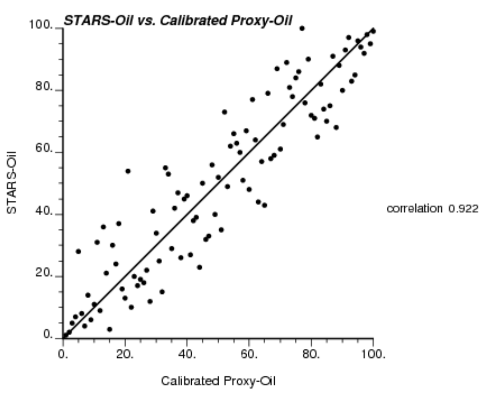

Figure 6: Comparing uncertainty range of cummulative oil and steam between simulator and proxy



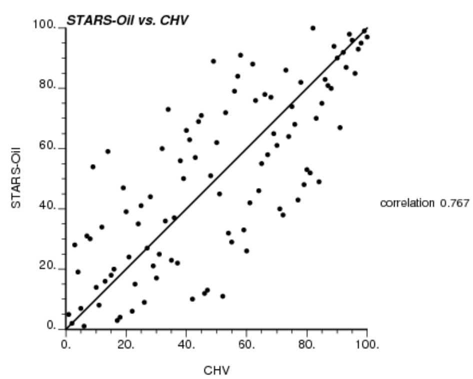

(a) Simulator oil vs. OOIP




(b) Sim. oil vs. uncalibrated proxy oil

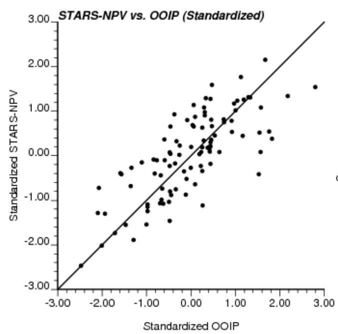



(c) Sim. oil vs. calibrated proxy oil

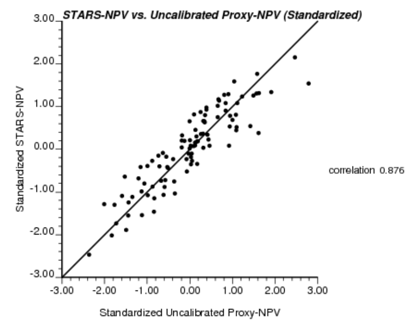



(d) Simulator oil vs. CHV

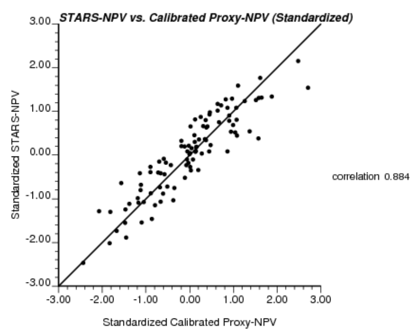
Figure 7: Correlation coefficient between cummulative oil results of simulator and other methods



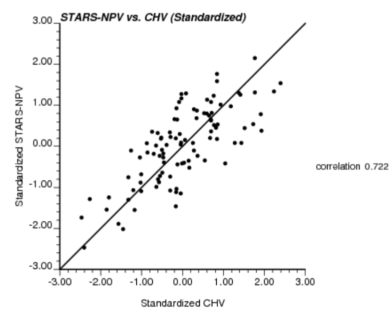

(a) Simulator NPV vs. OOIP




(b) Sim. NPV vs. uncalibrated proxy NPV

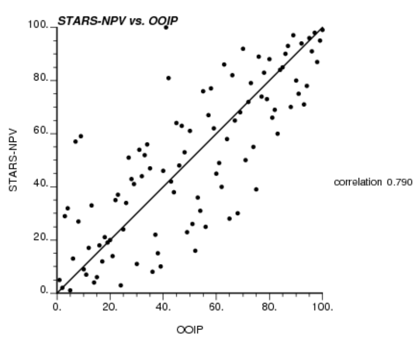



(c) Sim. NPV vs. calibrated proxy NPV

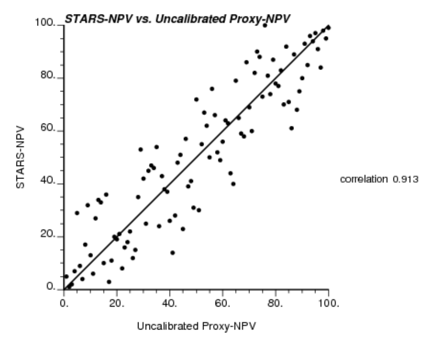



(d) Simulator NPV vs. CHV

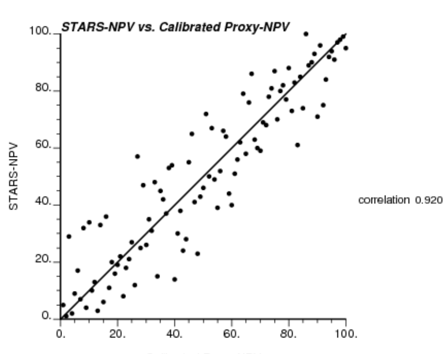
Figure 8: Correlation coefficient between NPV results of simulator and other methods (standardized)



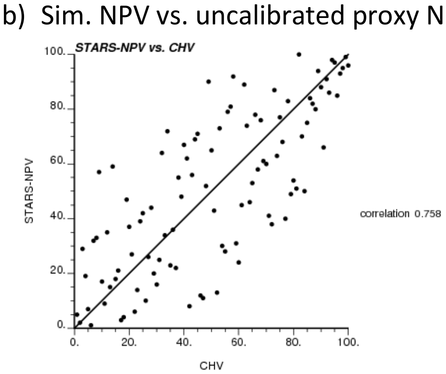

(a) Simulator NPV vs. OOIP




(b) Sim. NPV vs. uncalibrated proxy NPV




(c) Sim. NPV vs. calibrated proxy NPV




(d) Simulator NPV vs. CHV

Figure 9: Correlation between NPV results of simulator and other methods (zero discount rate)

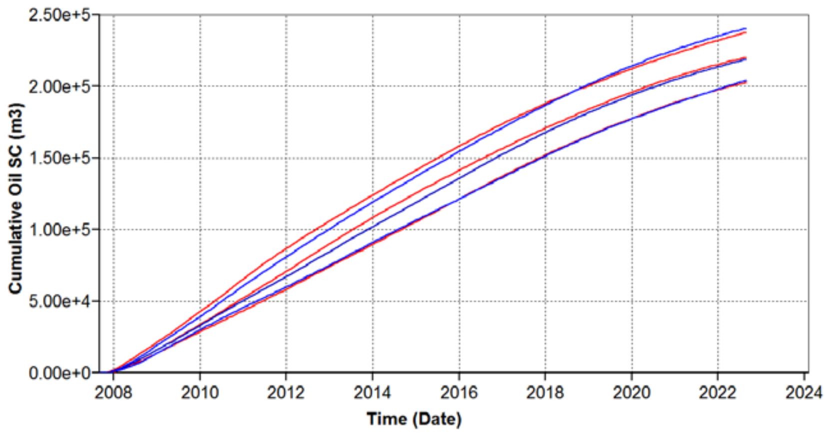



Figure 10: Comparison between cumulative oil production of simulator (red) and proxy (blue) for P10,P50 and P90 realizations

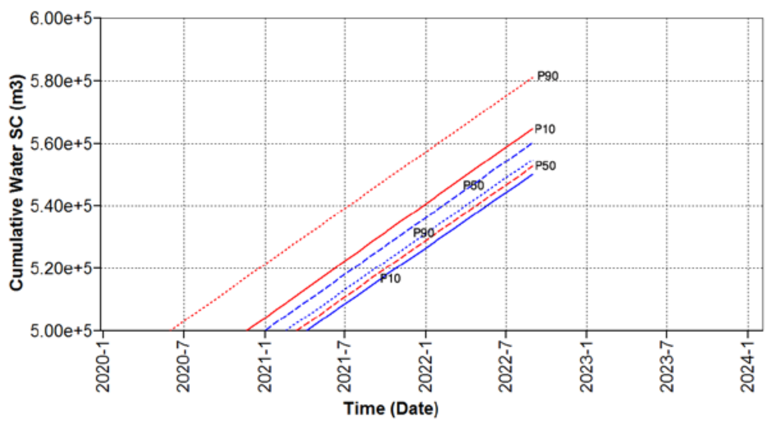



Figure 11: Comparison between cumulative steam production of simulator (red) and proxy (blue) for P10,P50 and P90 realizations for last 2 years of production

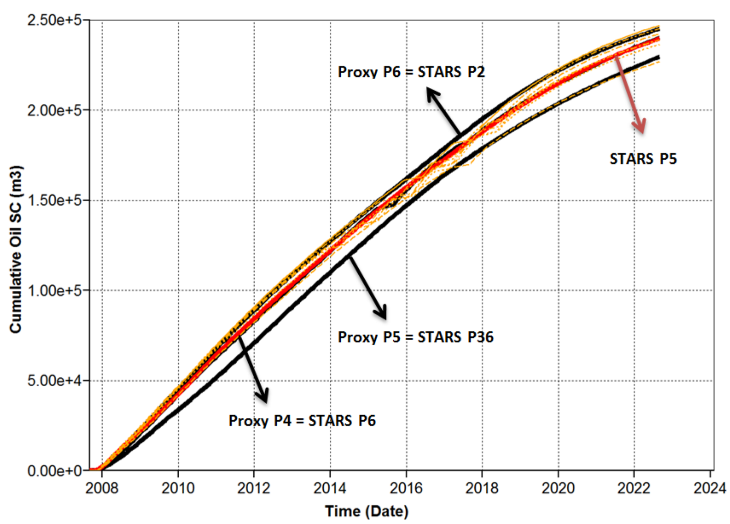



Figure 12: Combining 3 different realizations using different seed numbers. Yellow curves show cumulative oil production for different combined realizations. Red curve shows simulator P5, and black curves show cumulative oil production for P4, P5 and P6 proxy realizations.

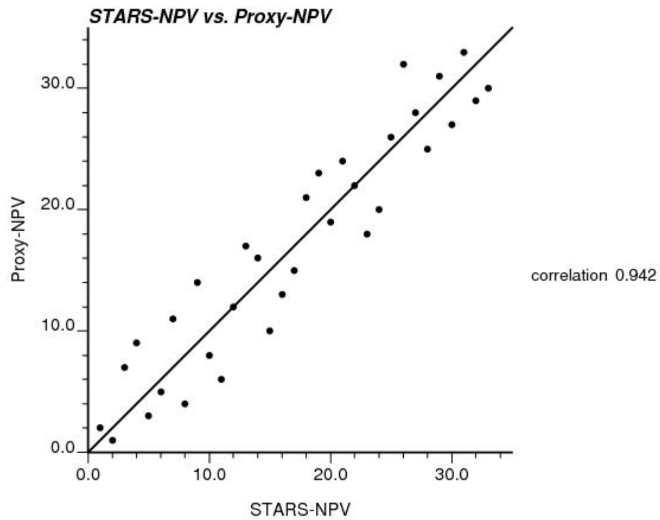



Figure 13: Re-ranked realizations after combining each three of original realizations together

Table 1: Corresponding simulator rank for P10, P50 and P90 of proxy realizations

| **Proxy** | **Simulator** |
|---|---|
| P10 | P12 |
| P50 | P34 |
| P90 | P89 |