INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN FLUIDS
Int. J. Numer. Meth. Fluids 2009; **61**:768–779
Published online 23 December 2008 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/fld.1982

Improving oil fields recovery through real-time water flooding optimization

Pamela Alessia Chiara Marescalco*, †

Politecnico di Torino, Land, Environment and GeoTechnologies Engineering Department, 24, C.so Duca degli Abruzzi, 10129 Torino, Italy

SUMMARY

Increasing oil recovery from reservoirs is a strong urge. One of the most effective ways to get the result is water flooding and that's why its application is nowadays widely used in the petroleum industry. Obviously, water flooding efficiency strongly depends on reservoir properties; this makes simulating a water injection process *a priori* an extremely important step of the reservoir production strategy. Simulation is commonly done adopting a finite difference (FD) simulation approach.

This paper explores a different and complementary approach, represented by streamline-based simulation, coupled with a tool to optimize water flooding campaigns and to help quick decision making. In the present study, water flooding simulation is performed via two commercial software: an FD and a streamline-based simulator, to highlight advantages and disadvantages of both simulation techniques in describing a water injection campaign and to exploit the two approaches' uniqueness in parallel.

The final goal of iteratively converging to the optimal water flooding scheme, which is the core of the present work, is achieved through a customized Matlab script. The generated automatic procedure shows its effectiveness in improving oil recovery, expediting decision making and saving time and FD simulation runs. A three steps workflow is outlined to get the best water flooding scheme for the examples shown below.

Received 13 March 2008; Revised 1 September 2008; Accepted 8 November 2008

KEY WORDS: water displacement optimization; FD simulation; streamline simulation; Matlab automated routine; real-time decision making; quantitative and iterative adjustment of water rates to be injected

INTRODUCTION

In the last decades water flooding has been widely applied in the petroleum field, both in mature and in newly developed fields, and its attractiveness lies in supporting the entire field pressure

*Correspondence to: Pamela Alessia Chiara Marescalco, Politecnico di Torino, Land, Environment and GeoTechnologies Engineering Department, 24, C.so Duca degli Abruzzi, 10129 Torino, Italy.
†E-mail: pamela.marescalco@polito.it

during depletion and in improving the final oil recovery [1–3]. The technique consists in injecting water with the purpose of displacing and therefore producing oil, especially if the reservoir lacks an underlying aquifer able to counterbalance the depletion and to drive oil to the producer wells.

To really understand a water flooding process and to predict its efficiency, it is useful to simulate it *a priori*. This is usually done via finite difference (FD) simulation, which is able to describe any kind of existing reservoir very accurately, but unfortunately is not able to give enough details about the way the flow occurs throughout the field. Recent works [4, 5] have proposed a newly developed approach, based on streamline simulation, whose main attraction lies in providing information not obtainable from FD simulation and useful for the purpose of improving reservoir performances. In the present study, water flooding simulation is performed via two commercial software: an FD and a streamline-based simulator, to highlight advantages and disadvantages of both simulation techniques in describing a water injection campaign and to exploit the two approaches' uniqueness in parallel. If FD simulation is essential to checking the streamline simulation results, the streamline-based simulator is, on the other hand, an ideal tool to perform a procedure able to optimize water injection. Then, the core of the work and its innovative approach lies in exploiting the two software features in conjunction with the application of a customized Matlab code developed in order to elaborate all the streamline simulation outputs, to calculate the changes to be made to the production/injection constraints for the subsequent simulation run, so as to iteratively converge to the optimal injection scheme for the reservoir under study. A three steps workflow is outlined to get the best water flooding scheme for the examples shown below.

FD APPROACH VERSUS STREAMLINE SIMULATION

ECLIPSE is a complete and complex simulator, whose attractiveness resides in being able to describe any kind of reservoir, including geological complexity, formation features, and fluid properties. The simulator is based on a time and spatial discretization and solves a three-dimensional equation by assigning to all the parameters involved in the simulation a unique value, associated with the entire cell, for every grid block. For models with a large number of cells, using FD relaxation can be computationally heavy; therefore, a good balance must be kept between having sufficient accuracy in describing the reservoir and keeping simulation time within reasonable limits [6].

3DSL, on the other side, solves two different equations on two different grids and this is usually faster than FD simulation, especially for large models: the pressure equation is solved implicitly on the background grid (or pressure grid), whereas the saturation equation is solved explicitly on the streamline grid. This involves a minor effect of grid refinement on the results of the simulation, time-step limitations not as severe, thanks to a better stability of the geometrical grid, numerical diffusion easier to control, faster solutions with respect to FD approach [7].

Streamline simulation solves mono-dimensional equations along streamlines, which means it solves multiple streamlines in parallel, and the fluid transport, which for FD approach occurs between grid cells [8], occurs along streamlines: this gives an immediate answer in terms of how the streamlines (connecting injector and producer wells—to say, well pairs) are distributed, so that the fluid trajectories and their rates at the wells are known at every time step [9, 10]. Thanks to the available information, the distribution of injected water volumes can be modified, and a more effective production strategy can be planned to maximize oil recovery [4, 5]. Same as for FD simulation, when using streamline-based simulation a good balance must be maintained between pressure updates and computational speed.

DOI: 10.1002/fld

In conclusion, 3DSL is simpler from a reservoir description (includes both flow physics and petro-physical/geological information) point of view, but it cannot take into account important parameters such as capillary pressure or cross flow effects: moreover, fluid compressibility cannot be easily taken into account and mass conservation errors may occur while mapping between pressure grid and streamline grid therefore being incomplete or inadequate for most of real reservoirs. Every further detail can be found in previous works [11].

THE IDEA OF THE STUDY

In this paper the use of the two software as complementary tools to optimize water injection is shown: ECLIPSE appeared to be the most reliable software to simulate reservoir models and to be essential to verify 3DSL's results accuracy upstream and downstream of the methodology developed for this research, while 3DSL has been shown to be simpler and usually faster, providing information not obtainable by means of FD simulation, and which could be exploited to save a trial-and-error process trying to find the best injection scheme.

The idea of the study resulted from previous works [12].

The research presented here follows a three step workflow. In the first part of the study, the two software were used to simulate simple synthetic models. Once the results obtained from the two simulators were checked for consistency, a method was developed to exploit 3DSL's features. The most interesting pieces of information available from 3DSL are the connections between well pairs (injector-producer) and the rates at the wells and the connections. With this information available, the streamline simulator, coupled with Matlab, was involved into an automatic procedure that reallocated water injected volumes in order to optimize water injection campaigns, for all the examined cases.

This was gained by a customized Matlab script, written for this specific purpose, which automatically interacted with the streamline simulator, processed the input data supplied by the software giving back new input rates to be used for the following simulation run. This was done for a fixed number of runs to iteratively converge to the optimal injection scheme. From preliminary analyses [13] the procedure was shown to be effective.

Eventually, in the third experimental phase, the last rates calculated from Matlab were input into ECLIPSE to check the procedure's effectiveness and the added value in terms of oil recovery improvement.

THE AUTOMATED PROCEDURE AND THE EXPERIMENTAL METHOD

Let's now focus on the second and main part of the experimental study which, as we said, consisted in writing a customized Matlab code. Streamline answers in terms of streamlines distribution (connecting injector and producer wells—or well pairs) and fluid rates at the wells are written at every time step in a 3DSL output file named *.WAF, which is crucial for the entire coding described below and for its application.

The endeavor of the Matlab customized code is the optimization of the displacement process through a gradual reallocation of injected water rates, carried out by increasing the water volume injected at the highly efficient connections and decreasing it at the poorly efficient connections. The term injection efficiency (for a well pair connection) stands for the ratio between offset oil

DOI: 10.1002/fld

produced thanks to water displacement and the amount of water injected at a certain well. In an analogue manner the injection efficiency of an injector well is the ratio between offset oil at all producers connected to it and the total water injected at the same well. The approach used for the current application was aimed at increasing the oil production through a better use of a given water volume available for injection. The Matlab code written for this purpose mainly works as follows: the data needed for the procedure are read from 3DSL's output *.WAF file and loaded into Matlab environment, then they are processed throughout the code; eventually new rates for the next simulation run are output to 3DSL. This is all done automatically with an approach aimed at maximizing oil production through a more efficient use of a given water volume available for the injection [13]. The code steps are here summarized [12]:

1st step consists in: establishing the number of iterations to be run for the procedure of rate reallocation and their duration; fixing the volume of water to be injected and the target liquid rate.

2nd step consists in: running a 'do nothing' 3DSL simulation in order to choose a proper starting time for the entire procedure of rate reallocation (usually the reallocation starts whereas a production plateau starts).

3rd step consists in: reading (within the Matlab environment, by means of functions coded on purpose) from the *.WAF file: rates (total rate for each injector well, and partial rate for each production well connected to the injector); time; name and number of injector or producer wells and connections between them; number of existing connections in the model at any time step of the simulation.

4th step consists in: calculating the injection efficiency for each well pair, for each injector well, and for the field (average injection efficiency).

5th step consists in: calculating for each iteration and for each injector well a new rate:

$$q_i^{\text{new}} = (1+w_i)\cdot q_i^{\text{old}} \tag{1}$$

where i stands for the well, w_i for the weight it has been assigned, and q_i^{old} for the rate injected at the well at the previous step.

The average reference field injection efficiency (referred to as signed e) is a mean value: depending on its value, positive or negative weights are assigned to the efficient or inefficient connections.

Once the maximum weight, minimum weight, minimum injection efficiency allowed, maximum injection efficiency awaited, and α (which is the grade of the polynomial that interpolates the relation weight-efficiency) are fixed, the weights are evaluated as follows:

$$e_i > \bar{e}:\ w_i = \text{MIN}\left(w_{\max}, w_{\max}\cdot\left(\frac{e_i-\bar{e}}{e_{\max}-\bar{e}}\right)^{\alpha}\right) \tag{2}$$

$$e_i < \bar{e}:\ w_i = \text{MAX}\left(w_{\min}, w_{\min}\cdot\left(\frac{\bar{e}-e_i}{\bar{e}-e_{\min}}\right)^{\alpha}\right) \tag{3}$$

where $w_{\min}$ is the minimum weight at the least efficiency, $w_{\max}$ is the maximum weight at the highest efficiency, $e_{\min}$ is the least acceptable injection efficiency, $e_{\max}$ is the highest awaited injection efficiency.

6th step consists in: calculating new rates for each well pair connection and, consequently, for each injector; calculating for each injector the differences between the last known rates and the new ones; determining the new total volume of water injected as a summation of the new rates at the injectors; checking that the constraints on the total water volume available (x) are satisfied by

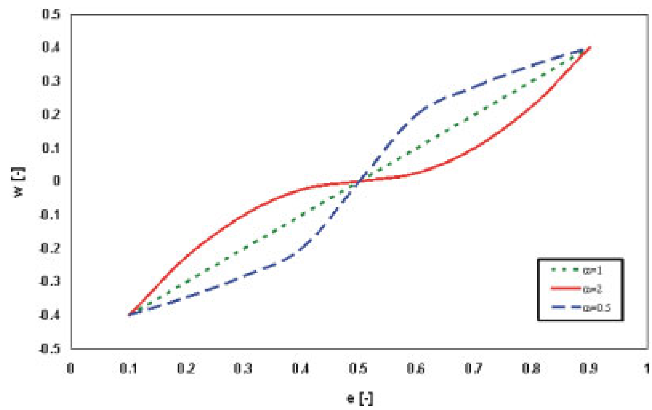

Figure 1. Weighting functions (as from Equations (2) and (3)) for different values of exponent α.

introducing a correction factor c:

$$c = \frac{x}{\sum q_i^{\text{new}}} \tag{4}$$

7th step consists in: calculating new liquid rates (for each producing well the novel rate is calculated by adding/subtracting the same amounts of water rate, $\Delta q \pm$, calculated for the injector wells connected to it), imposing that the constraints on the total liquid volume (y) are satisfied through the correction factor $c1$:

$$c1 = \frac{y}{\sum q_i^{\text{new}}} \tag{5}$$

8th step consists in: making Matlab write a text file to be included in the 3DSL dataset, summarizing all the new rates and time information.

9th step consists in: running the reallocation procedure, following the eight steps listed above, for as many iterations as initially fixed (well rates and time are updated at every Δt).

Both Δt and the set of parameters chosen at the 5th step affect the final results.

For all the examples shown here, to signed e was allotted the average field efficiency value, in order to have a case sensitive value. At the same time, α was put equal to 2 for all the examined cases, so that the weighting function would be nonlinear and the most significant changes in injection rates would occur far-off from the average efficiency, while only small changes would take place around the mean value (Figure 1).

For the examples shown below, parameter sensitivities were performed in order to get the best set for the application of the Matlab code.

RESERVOIR MODELS DESCRIPTION

In this paper two synthetic models and a real one are presented.

The numbers of cells for the synthetic models are $20 \times 20 \times 1$ for the first case, and $123 \times 54 \times 1$ for the second case. A uniform discretization of the volume was chosen to accurately describe the

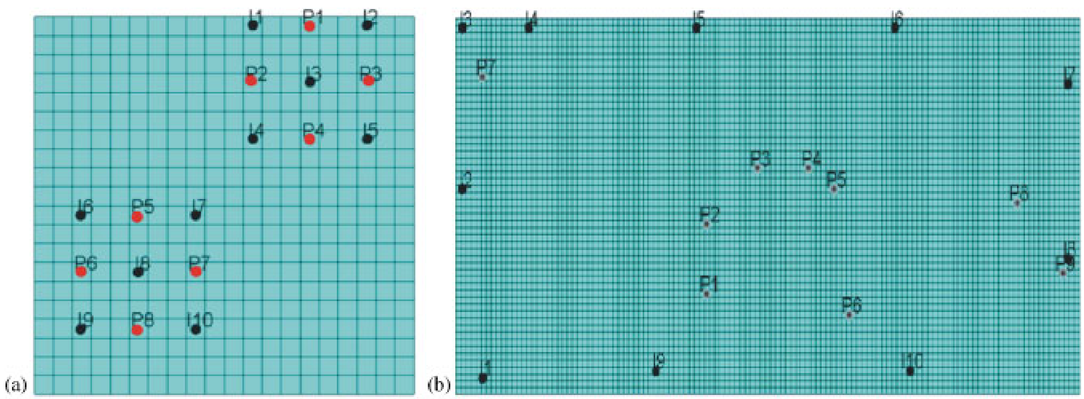

Figure 2. Well locations: model one (a) and model two (b).

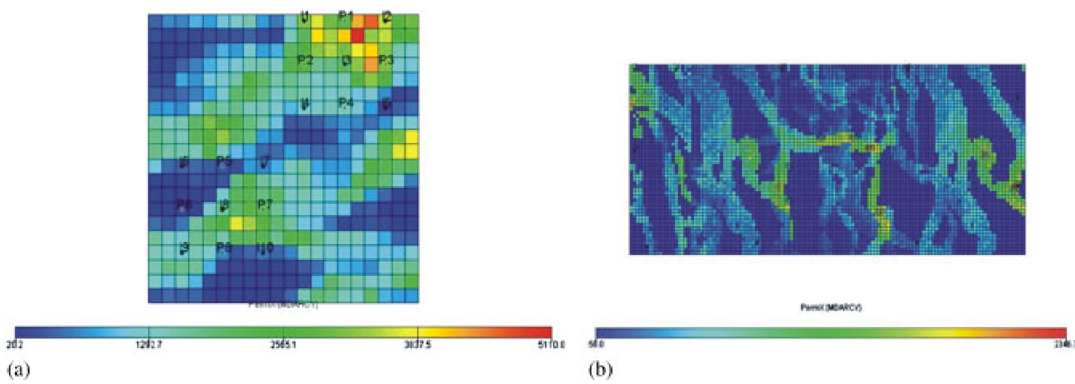

Figure 3. Permeability map: model one (a) and model two (b).

pressure disturbance and the fluid flow. The grid block dimensions are $100\,\mathrm{m} \times 100\,\mathrm{m} \times 500\,\mathrm{m}$ and $50\,\mathrm{m} \times 50\,\mathrm{m} \times 500\,\mathrm{m}$, respectively. The wells, all vertical, are positioned as in the patterns shown in Figure 2(a, b), in order to exploit the highest permeability zones (Figure 3(a, b)).

The phases present in both models are water and oil, which is supposed to be dead oil. Both water and oil have the same viscosity, equal to 1 cp. Oil and water density are, respectively, 780 and $1029\,\mathrm{kg/m^3}$. Datum pressure is equal to 30 bars. For both models, water and liquid constraints are set equal, to let the displacement occur by voidage replacement, and correspond to $80.000\,\mathrm{rm^3/day}$ and to $150.000\,\mathrm{rm^3/day}$, respectively. For both models the reallocation procedure starts at day 730; the number of steps, whose duration is 730 days each, is equal to 10.

Similarly a real field was tested. The model was available from ECLIPSE; a translation work was done to obtain a model written for 3DSL. The two models were then checked to verify the coherence of the main parameters. Once the match was gained, 3DSL model was used to apply the procedure. The real model, as shown in Figure 4(a, b), is divided into three regions by the presence of faults.

DOI: 10.1002/fld

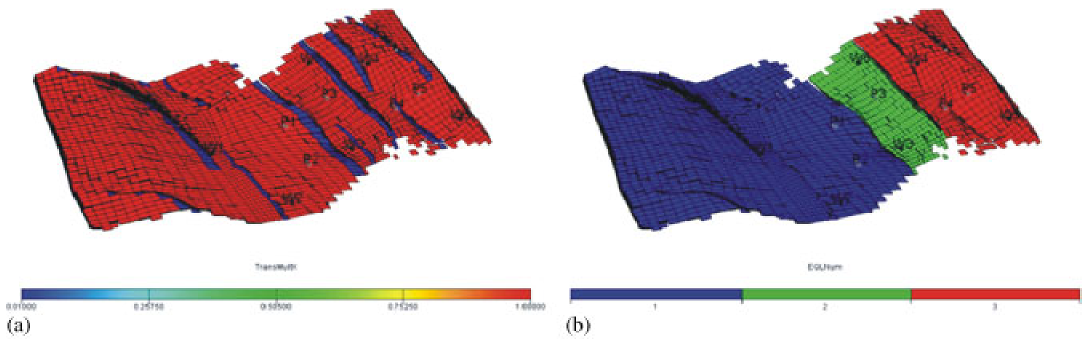

Figure 4. (a) Faults divide model three into three regions and (b) model three has three different regions.

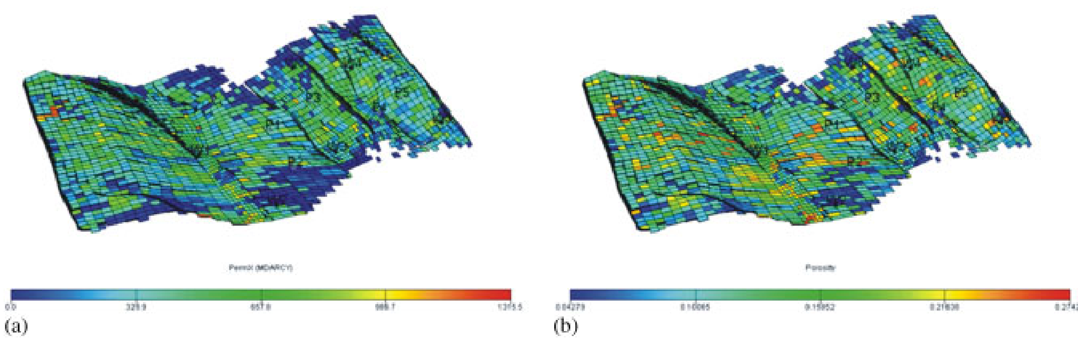

Figure 5. Permeability (a) and porosity map (b). Model three.

Table I. Model three: PVT data.

PVT properties
$B_o = 1.75\,\mathrm{rb/stb}$
$\mu_o = 1\,\mathrm{cP}$
$\mu_w = 0.31\,\mathrm{cP}$
$\rho_o = 52.7\,\mathrm{lb/ft^3}$
$B_w = 1.03\,\mathrm{rb/stb}$
$C_w = 2.4 \times 10^6\,\mathrm{psi^{-1}}$
$\rho_w = 64.04\,\mathrm{lb/ft^3}$

The number of cells is $68 \times 71 \times 23$. The grid cells are not uniform. Permeability and porosity are highly heterogeneous and range from 0 to 1315 mD and from 4 to 27%, respectively (Figure 5(a, b)).

The other model properties are summarized in Tables I and II.

DOI: 10.1002/fld

Table II. Model three: main parameters.

S_{wi} (three regions)	0.13; 0.29; 0.06
C_f(psi^{-1})	3×10^{-6}
Datum depth (ft)	8953
Datum pressure (psi)	5212
Reservoir temperature (F)	233
Bubble point (psi)	4551@datum depth
Oil water contact (ft)	9965
Oil/water rate (stb/day)	90 000
Production (years)	20

RESULTS

The three models examined were all used for the three steps workflow related before.

First of all, the match and coherence between the two models were always obtained. At this point no relevant discrepancies were observed between the two sets of results for the three models. Figure 6(a, b) shows, respectively, oil and water cumulative production from the third model only, as an example.

At a second stage, Matlab code was applied to each 3DSL model, starting from a certain moment in time, fixed at day 730 for all the three examples. Ten iterations were run, each of them lasting 730 days, and the total time for the procedure to run was fixed so as to be compared with the base case 'do nothing' simulation run.

As for the frequency of the injection update, the longer the time step is, the higher the rates injected/produced and the major the changes concerning the values of well pairs injection efficiencies during the time steps. For the present work the well pairs injection efficiencies were assumed to remain constant throughout the single time step. Shorter time steps would maybe more suitable to this hypothesis but, on the other hand, they would imply a much higher computational time. In a real field application it might be useful to try with medium time steps (i.e. 6 months), eventually shortening them if, by analyzing the real-time field data, an intervention would appear to be needed.

Each model was then compared with its respective optimized case, as shown in Figures 7–9(a, b).

The figures again show, respectively, oil and water cumulative production from the field for the three models in sequence. For all the models the generated methodology was shown to give good results and to carry advantages with respect to the mere base case.

The two synthetic cases showed good results both in terms of a relevant improvement in oil recovery and of a significant reduction in water production (the results are summarized in Tables III–V). Figure 10(a, b) shows the displacement of model two at the end of the simulation, for the base case and for the reallocated rates case, respectively.

The real case, which at the time of this research was a pure forecast example, since the reservoir was not producing, so no production history was available, showed to gain a certain amount of oil production, but in parallel a higher water production.

At the third stage the final rates observed from the 3DSL 'optimized' case were input in ECLIPSE, to double check the effectiveness of the optimization for the specific case. Figure 11(a, b)

DOI: 10.1002/fld

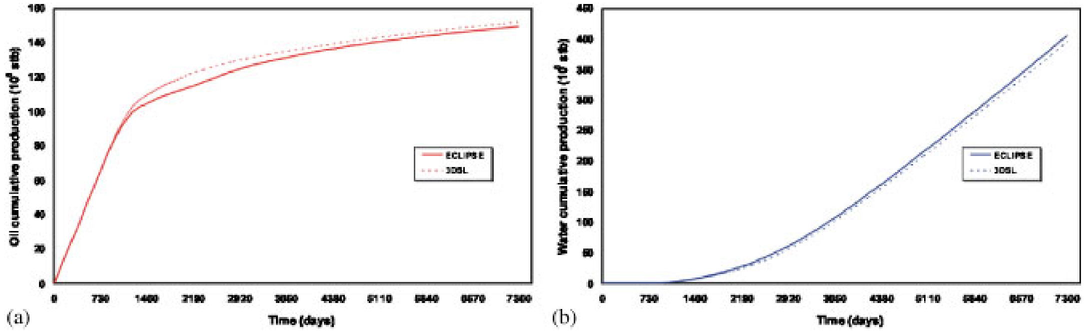

Figure 6. Match ECLIPSE versus 3DSL: oil (a) and water cumulative production (b). Model three.

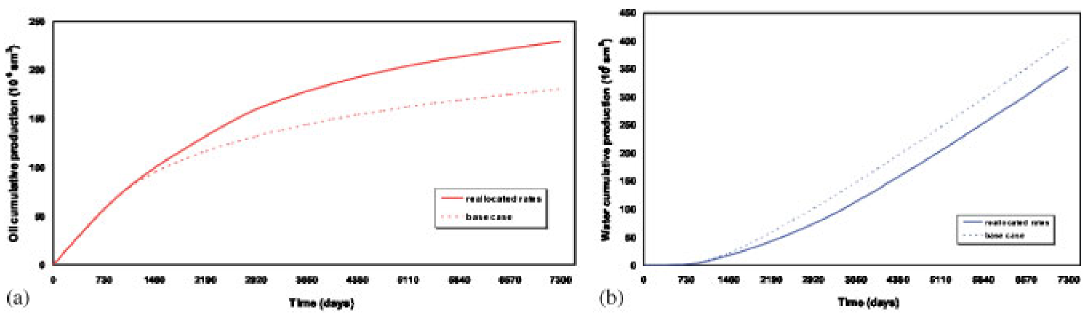

Figure 7. Base case versus reallocated rates case: oil (a) and water cumulative production (b). Model one.

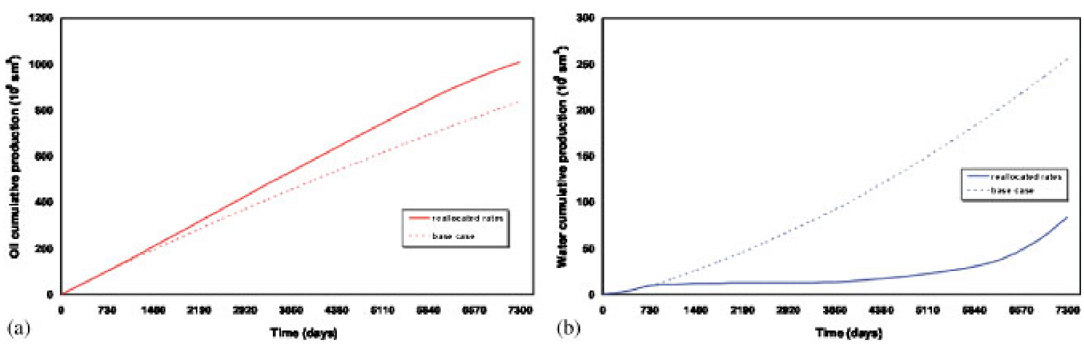

Figure 8. Base case versus reallocated rates case: oil (a) and water cumulative production (b). Model two.

DOI: 10.1002/fld

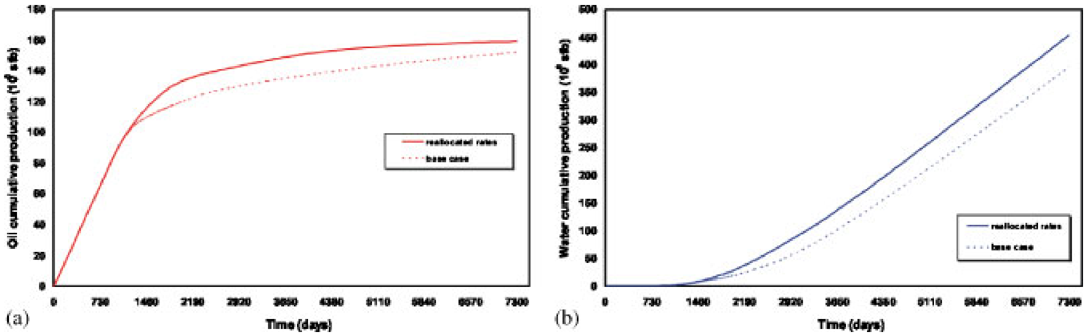

Figure 9. Base case versus reallocated rates case: oil (a) and water cumulative production (b). Model three.

Table III. Model one: oil and water relative difference.

3DSL	N_p ($10^6\,\mathrm{sm}^3$)	W_p ($10^6\,\mathrm{sm}^3$)
Base case	180.5	403
Reallocated rates case	230	354
$\Delta N/\Delta W$	+21.5%	−12%

Table IV. Model two: oil and water relative difference.

3DSL	N_p ($10^6\,\mathrm{sm}^3$)	W_p ($10^6\,\mathrm{sm}^3$)
Base case	839	255
Reallocated rates case	1010	84
$\Delta N/\Delta W$	+17%	−67%

Table V. Model three: oil and water relative difference.

3DSL	N_p ($10^6\,\mathrm{stb}$)	W_p ($10^6\,\mathrm{stb}$)
Base case	152	454
Reallocated rates case	159	397
$\Delta N/\Delta W$	+4.4%	+12.5%

shows oil and water cumulative production for the second synthetic model, obtained with ECLIPSE before and after the reallocation procedure.

For the synthetic models, whose ECLIPSE results downstream of Matlab procedure are as good as expected, the methodology proved to be valid.

DOI: 10.1002/fld

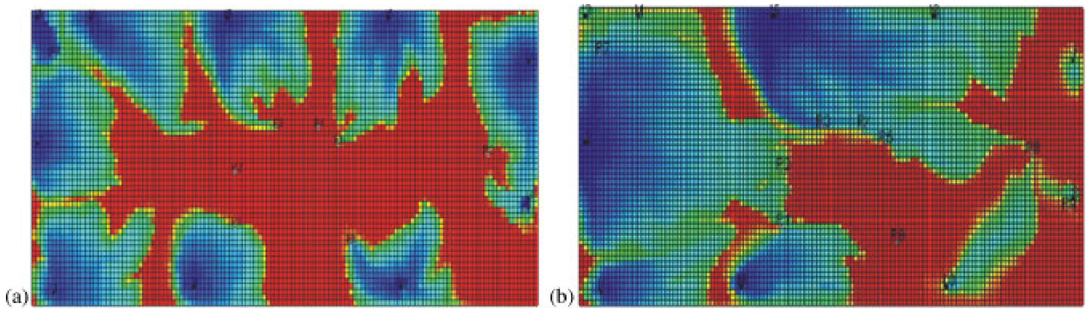

Figure 10. Oil displaced at the end of the simulation run: base case (a) and reallocated rates case (b). Model two.

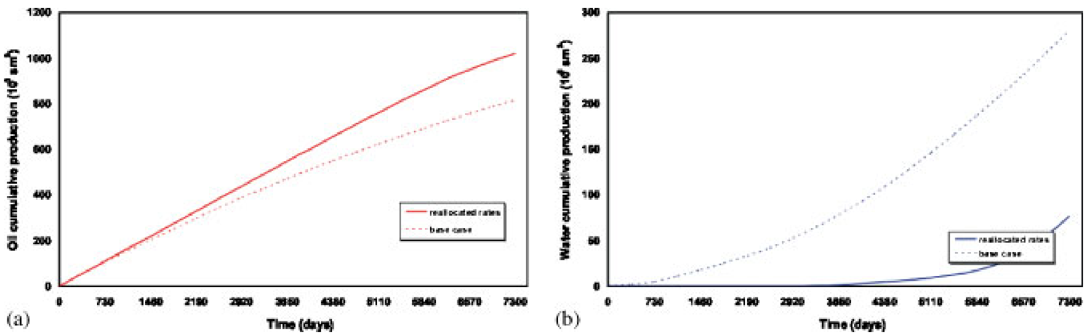

Figure 11. Reallocated rates case versus base case, ECLIPSE check simulation run, oil (a) and water cumulative production (b). Model two.

As for the real case, the results at this stage are not as good as expected. In the next paragraph a few comments on this will be remarked.

DISCUSSION AND CONCLUSIONS

Looking at the results, it can be generally said that the Matlab code written for this study has added value to the reallocation procedure, making it reliable and attractive for its application in the petroleum industry. Previous works [12] conducted for fields under production and the two simpler examples reported here undoubtedly proved that reallocating water to optimize water injection is effective both for models with simpler reservoir features (incompressible fluids, simple geology) and for more complex cases (compressible fluids, heterogeneous formation): an increased oil production was observed together with a reduced water production.

As stated in the previous paragraph, for the real model, the optimized case with respect to the base case shows a good improvement in oil recovery, but a parallel higher water production: the field in fact had not yet been deployed, so no real-time production neither geological nor petrophysical information was provided. The reservoir features and the specific values assigned to the main reservoir parameters were then simply estimated: the values assigned to model parameters were a choice among other equally valid assessments. Last but not the least, ECLIPSE's results certainly depend on the large amount of modifications done with respect to the original ECLIPSE model, modification necessary in order to comply with 3DSL's binding simplifying hypotheses at the time the model 'translation' was done.

The aim of the research work of developing a completely automatic procedure to find the best scheme for the volumes to be injected and of using 3DSL coupled with Matlab and ECLIPSE as complementary tools proved to be effective and valid. The entire work represents a real help when a quick decision on a water flooding arrangement has to be made, both for injection campaigns yet to plan or for injection operations to be adjusted.

If a reallocation procedure was to be performed only by means of ECLIPSE, a trial-and-error procedure would be needed, with a considerable waste of computational time and simulation runs. On the other hand, 3DSL allows for more simulations in parallel, saving computational time and redundant simulations.

The present research in the future can be extended to a real case with a known production history to calibrate the best injection scheme.

ACKNOWLEDGEMENTS

The author acknowledges Schlumberger-GeoQuest and Streamsim Technologies, Inc. for providing the software used in this research; she also acknowledges Alberto Cominelli from ENI and Prof. Francesca Verga from Politecnico di Torino, for the joined research project she had the chance to work on during her PhD (mainly years 2005 and 2006) and Marco Thiele from Streamsim for the support and consulting.
Note of the author: The author would like to highlight that in parallel and after her PhD work, Streamsim Technologies, Inc. went on with new software releases and that the procedure here described is qualitatively done by a new release of the software the author used under older releases. The difference is that the procedure developed by the author is measurable step by step. What is remarkable is that the utility of the routine has been widely commercially proven.

REFERENCES

1. Craig Jr FF. *The Reservoir Engineering Aspects of Waterflooding*. SPE Monograph, vol. 3, H. L. Doherty Memorial Fund of AIME. Society of Petroleum Engineers of AIME, 1971.
2. Dake LP. *Fundamentals of Reservoir Engineering*. Elsevier: Amsterdam, 1978.
3. Whillhite GP. *Waterflooding*. Textbook Series, vol. 3. Society of Petroleum Engineers, 1986.
4. Thiele MR. Streamline simulation. *Proceedings of the 6th International Forum on Reservoir Simulation*, Schloss Fuschl, Austria, 2001.
5. Thiele MR. Streamline simulation. *Proceedings of the 7th International Forum on Reservoir Simulation*, Baden-Baden, Germany, 2003.
6. Schlumberger GeoQuest. *Eclipse 100 Reference Manual*. Schlumberger Houston, 2004.
7. Streamsim Technologies, Inc. *3DSL User Manual*. Streamsim Technologies, Inc., San Francisco, CA, 2005.
8. King M, Datta-Gupta A. *Streamline Simulation*: *A Current Perspective*. Marcel Dekker: New York, 1998.
9. Batycky RP, Blunt MJ, Thiele MR. A 3D field scale streamline simulator with gravity and changing well conditions. *Proceedings of the Annual Technical Conference and Exhibition*, Denver, Co, 1996. Paper SPE 36726.
10. Batycky RP. A three-dimensional two-phase field scale streamline simulator. *Ph.D. Dissertation*, Department of Petroleum Engineering, Stanford University, Stanford, CA, 1997.
11. Marescalco PAC. Ottimizzazione dei processi di iniezione d'acqua nei giacimenti petroliferi. *Ph.D. Dissertation*, Politecnico di Torino, 2007.
12. Thiele MR, Batycky RP. Using streamline-derived injection efficiencies for improved waterflood management. *SPEREE*, vol. 9, No 2, April 2006; 187–196 (SPE84080-PA).
13. Marescalco PAC, Verga F, Cominelli A. Is there an optimal approach to simulate water flooding? *Fifteenth International Symposium on Mine Planning and Equipment Selection*, Turin, Italy, 20–22 September 2006.