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# Reservoir management using streamline-based flood efficiency maps and application to rate optimization ☆

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ABSTRACT

3-D streamlines provide an effective tool for reservoir management because of their ability to display reservoir flow and well connections in a physically intuitive manner. Streamlines have been extensively used to investigate the interaction between heterogeneity and well patterns and also for rate allocation and pattern balancing. More recently, streamlines have been used in conjunction with constrained optimization techniques for improving waterflood performance via rate control. Field scale rate optimization problems, however, involve highly complex reservoir models, production and facilities constraints and a large number of unknowns, making them inaccessible for routine waterflood management.

In this paper we provide a simple and easy to use workflow for waterflood rate optimization using streamline-based flood efficiency maps that display the flux and time of flight distribution amongst producing wells. We demonstrate the use of flood efficiency map to optimize the injection/production rates to maximize waterflood sweep efficiency by equalizing the average time of flight (TOF) amongst the producing wells in regional basis. Our optimization approach is extremely efficient because it relies on simple analytic calculations to compute weighting factors for injection and production rates to minimize the TOF variance amongst producing wells. Because the approach does not rely on formal and complex optimization tools, it is particularly well-suited for large-scale field application. Also, the approach can be used with both streamline and finite difference simulators. For finite-difference simulations, the streamlines and time of flight are derived from the flux field generated by the simulator. Multiple examples are presented to support the robustness and efficiency of the proposed waterflood management scheme. These include 2D synthetic examples for validation and a 3D field application.



## 1. Introduction

Streamline technologies have been widely used for reservoir management because of its powerful flow visualization capabilities that allow us to analyze rate allocation, pattern balance and waterflood performance. The connected flux volumes and its relative distribution can be easily obtained in terms of allocation factors from the streamlines. The application of streamlines has been extended to quantitatively analyze and optimize sweep efficiency using the streamline time of flight (TOF) distribution (Alhuthali et al., 2007, 2010). In terms of early application to rate optimization, Grinestaff (1999) used streamline flow visualization to infer inefficiencies in the waterflood and set injection targets. No formal optimization was used here. Well rates were adjusted manually to obtain a more uniform distribution of streamlines amongst the producing wells. Grinestaff (1999) used allocation factors as their primary criterion for optimizing waterflood sweep. Thiele and Batycky (2003) proposed a streamline-based injection efficiency to optimize water injection. The injection efficiency was defined as the ratio of offset oil production to water injection as computed from the streamline-based flux distribution. More recently, Alhuthali et al. (2007) presented a rate optimization approach to maximize sweep efficiency through equalizing the waterflood front arrival times at the producing wells. They derived well rate allocation and optimized flood-front management by delaying the water breakthrough at the producing wells. This approach, however, requires calculation of sensitivity of arrival time with respect to production/injection rates and use of constrained optimization methods such as the sequential quadratic programming technique.

In this paper we follow-up on the previous work of Alhuthali et al. (2007, 2010) and propose a rapid and easy to use method to optimize production/injection rates. The goal here is to avoid use



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**Nomenclature**

| | |
|---|---|
| $\bar{\tau}_{ij}$ | average total TOF for the connection between well $i$ and $j$ |
| $\alpha_{ij}$ | global update coefficient for the connection between wells $i$ and $j$ |
| $\beta_{ij}$ | local update coefficient for the connection between wells $i$ and $j$ |
| $q_{ij}$ | total flux for the connection between wells $i$ and $j$ |
| $n_{sl,ij}$ | number of streamlines for connecting wells $i$ and $j$ |
| $\tau_{ijk}$ | $k$th streamline's total TOF in the connection between wells $i$ and $j$ |
| $\alpha_{ijk}$ | $k$th streamline's global update coefficient for connection between wells $i$ and $j$ |
| $\alpha_{ijl}$ | $l$th streamline's global update coefficient for connection between well $i$ and $j$ |
| $S_{ij}$ | sensitivity coefficient: changes in arrival time at producer $i$ with respect to change in flow rate of well $j$ |
| $N_{fsl,i}$ | number of fast streamlines between wells $i$ and $j$ |
| $S_w$ | water saturation, fraction |
| $S_{wf}$ | water flood front saturation, fraction |
| $f_w$ | fractional flow, dimensionless |
| $s(X)$ | slowness |

of complex optimization tools; rather we emphasize the visual and the intuitive appeal of the streamline method. The basic underlying principle here is similar to that of Alhuthali et al. (2007, 2010) and relies on two main ideas: (i) equalizing 'average time of flight' to all producers (ii) and minimizing the 'time of flight variance' within the streamline bundle. To accomplish this, we propose an easy to implement method for rate optimization utilizing streamline-based flood efficiency map. The flood efficiency map shows how the producers/injectors are connected and the relative movement of the flood front towards the producing wells. It consists of two areal maps: a flux distribution map and a time of flight distribution map. Although, the flux distribution maps have been used in the past to visualize flow, the use of TOF distribution map is novel. Using a combination of these two maps, we propose a procedure to optimize flood efficiency without the use of formal optimization tools. The main advantage of the proposed approach is that it is analytic, easy to implement and well-suited for large-scale field applications. The simple analytic approach allows the optimization can be carried out in a step-wise manner using a spreadsheet type application as opposed to construction of formal optimization frame which may often results in difficultness on reaching optimum solution especially if it includes large number of wells for optimization. Another advantage is its intuitive nature; we can visually examine the flow patterns as the calculations progress. The one limitation of the proposed approach is that it cannot impose hierarchical facility related constraints as implemented by Alhuthali et al. (2007) using the sequential quadratic programming.

This paper is organized into three sections that detail the theory and application of production and injection rate optimization. In the first section, we briefly outline the approaches and illustrate the procedural steps using a synthetic example. Production rate optimization approach is discussed first followed by the injection rate optimization approach. Next, we expand on the background and mathematical formulation underlying the proposed optimization method. Finally, we demonstrate the practical feasibility of our approaches using 3D field applications.

## 2. Approach

Our proposed method follows a simple and easy to use workflow using streamline-based flood efficiency map. The flood efficiency map, as shown in Fig. 1, is composed of two areal maps: a flux distribution map and a time of flight distribution map. Each of these maps can be generated from readily available streamline properties viz. the flow rate associated with each streamline and the time of flight along the streamlines. The flood efficiency map is a visual and physically intuitive tool for analyzing reservoir flow patterns and we extend its application to rate optimization. Specifically, we define two separate workflows for rate optimization: one is for production rate optimization and the other is for injection rate optimization. Depending upon the needs and the field conditions, one might want to utilize either or both to enhance waterflood efficiency.

### 2.1. Production rate optimization

The production rate optimization consists of two steps: (i) computing weighting factors for the production rates to equalize 'average TOF' at producers and (ii) minimizing the TOF variance within the streamline bundle reaching individual producers. First, we utilize the relationship between streamline flow rates and the TOF to compute rate change coefficients. We apply these rate change coefficients for the minimization of the 'global' TOF variance in a field- wide or regional basis by equalizing the 'average TOF' between producing wells. Second, we calculate weighting factors for 'local' update to further minimize the TOF variance by focusing on individual well connections and its bundle of streamlines.

Because the flood efficiency map provides all necessary information including flux and average TOF, the optimization can be carried out in a step-wise manner using a spreadsheet type application. The ease of implementation and the simplified nature of the workflow are the major strengths of our proposed approach. Below, we outline the production rate optimization in a stepwise manner.

(1) *Flow simulation and streamline tracing*. For flow simulation, we can use either a streamline simulator or a finite difference (FD) simulator. If we use a FD simulator, we need to perform streamline tracing using the fluid flux information from the FD simulator.
(2) *Streamline-based flood efficiency map construction*. We aim to display the key information related to flow patterns and reservoir sweep with the flood efficiency map as shown in Fig. 1. It includes a flux distribution map and an average TOF distribution map that enable us to optimize waterflood management. The streamlines connecting each injector–producer pair is depicted with a single representative streamline, the fastest streamline. The TOF distribution map displays the 'average TOF' between the well pairs. The average TOF is calculated by a simple arithmetic average of time of flight associated with all the streamlines for each connection. The flux distribution map displays volumetric flux between connecting wells computed by summing the fluxes carried by the streamlines. The flux distribution map is colored by the total flux connecting the wells while the color in TOF distribution map displays the average TOF. Thus, the flood efficiency map is