Streamline Simulation

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ABSTRACT

Streamline-based flow simulation (SL) has received significant attention over the past 5 years, and is now accepted as an effective and complementary technology to more traditional flow modeling approaches such as finite differences (FD). Streamline-based flow simulation is particularly effective in solving large, geologically complex and heterogeneous systems, where fluid flow is dictated by well positions and rates, rock properties (permeability, porosity, and fault distributions), fluid mobility (phase relative permeabilities and viscosities), and gravity. Capillary pressure effects, surface group constraints and expansion-dominated systems, on the other hand, are not modeled efficiently by streamlines.

Modern SL simulation rests on 6 key principles: (1) tracing three-dimensional (3D) streamlines in terms of time-of-flight (TOF); (2) recasting the mass conservation equations along streamlines in terms of TOF; (3) periodic updating of streamlines; (4) numerical 1D transport solutions along streamlines; (5) accounting for gravity effects using operator splitting; and (6) extension to compressible flow. These principles are reviewed here.

The usefulness and uniqueness of SL simulation is presented in the context of what are generally considered important issues in reservoir simulation: (1) upscaling; (2) quantifying displacement efficiency; (3) computational speed; (4) history matching; and (5) field optimization. In addition, novel, streamline-specific data is discussed in the context of injector/producer efficiencies and as a unique aid in upscaling by allowing engineers to go beyond the usual approach of only matching reference solutions.

Finally, the outlook for streamline-based simulation is discussed in the context of compositional simulation, tracing streamlines through structurally complex geometries, fractured systems, and parallel computation. The speed and efficiency as well as the availability of new data make streamlines potentially the most significant tool for solving complex optimization problems related to history matching and optimal well placements.

HISTORICAL CONTEXT

The current popularity of SL simulation should more aptly be termed a resurgence, given that streamlines—as pertaining to modeling subsurface fluid flow and transport—have been in the literature since Muskat and Wyckoff's 1934 paper and have received repeated attention since then. It is not the author's intention to give a full review of the technology in this paper. The interested reader is referred to the many papers in the literature having an extensive discussion and reference list (Crane et al., 2000; King and Datta-Gupta, 1998; Batycky et al., 1997). From the many different ideas and applications over the last 60 years, six key ideas have clearly emerged as the basis for the current state-of-the-art of the technology. These ideas are discussed in detail.

Key Idea #1: Tracing Streamlines in Three Dimensions Using Time-of-Flight

One distinguishing feature of current SL simulation is that the streamlines are truly 3D, rather than 2D as in the streamtube methods of the 70's and 80's. While streamlines are generally depicted from a birds-eye perspective and therefore might appear as being 2D, streamlines now correctly account for the previously missing vertical component of the flow description and are therefore fundamental to the current success of the technology. From a very practical point of view, the use of 3D streamlines no longer require geological models to be transformed into pseudo 2D areal models. In other words, streamlines are no longer tied to individual layers, but are truly 3D lines that can cut across simulation layers.
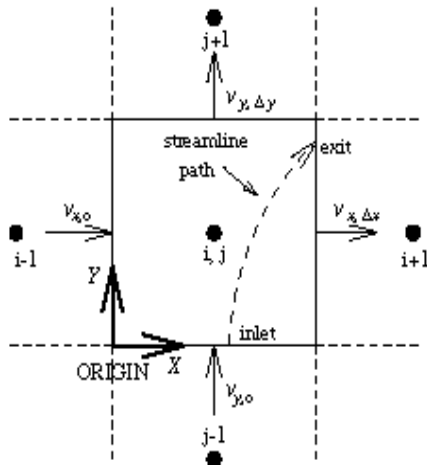
Figure 1: *Pollock's 3D tracing method through a Cartesian cell. Given an arbitrary entry point, the time to exit and the exit point can be determined analytically (from Batycky et al. 1997).*

The breakthrough work for tracing streamlines efficiently in 3D was that of Pollock (1988). Pollock's method is simple, analytical, and is formulated in terms of time-of-flight (TOF). To apply Pollock's method to any cell, the total flux in and out of each boundary is calculated using Darcy's Law. With the flux known, the algorithm centers on determining the exit point of a streamline and the time to exit given any entry point assuming a piece-wise linear approximation of the velocity field in each coordinate direction. The equations are simple: if v is the interstitial velocity ($v=u/\phi$), then a linear velocity description in the x-direction gives

$$v_x = v_{x0} + g_x(x - x_0); \qquad g_x = \frac{v_{x\Delta x} - v_{x0}}{\Delta x}$$

where v_{x0} is the x-velocity at $x=x_0$, and g_x is the velocity gradient in the x-direction. Since $v_x = dx/dt$, we can integrate the expression of the x-velocity (and in analogous fashion in the y- and z-direction) to get the exit times out of each face given an arbitrary entry point (x_i, y_i, z_i)

$$\Delta t_x = \frac{1}{g_x}\ln\left[\frac{v_{x0}+g_x(x_e-x_0)}{v_{x0}+g_x(x_i-x_0)}\right]; \qquad \Delta t_y = \frac{1}{g_y}\ln\left[\frac{v_{y0}+g_y(y_e-y_0)}{v_{y0}+g_x(y_i-y_0)}\right]; \qquad \Delta t_z = \frac{1}{g_z}\ln\left[\frac{v_{z0}+g_z(z_e-z_0)}{v_{z0}+g_z(z_i-z_0)}\right]$$

and exit coordinates x_e, y_e, and z_e. Since the streamline must exit from the face having the smallest travel time, $\Delta t_m = MIN(\Delta t_x, \Delta t_y, \Delta t_z)$, the exit locations are easily calculated by re-solving for x_e, y_e, and z_e using the minimum time:

$$x_e = \frac{1}{g_x} \ln[v_{xi} \exp(g_x \Delta t_m) - v_{x0}] + x_0$$

$$y_e = \frac{1}{g_y} \ln[v_{yi} \exp(g_y \Delta t_m) - v_{y0}] + y_0$$

$$z_e = \frac{1}{g_z} \ln[v_{zi} \exp(g_z \Delta t_m) - v_{z0}] + z_0$$

Pollock's equations are derived assuming orthogonal grid blocks, but very few real reservoirs models use such a strict Cartesian framework anymore. Using an isoparametric transformation, it is possible to transform corner-point geometry grids (CPG) into unit cubes, apply Pollock's method, and then transform the exit coordinate back to physical space. Details of this transformation are given by Prevost et al. (2001) and by Cordes & Kinzelbach (1994). Using Pollock's method and modifications thereof it is possible to trace streamlines through any realistic grid used in reservoir simulation (Prevost et al. 2001).
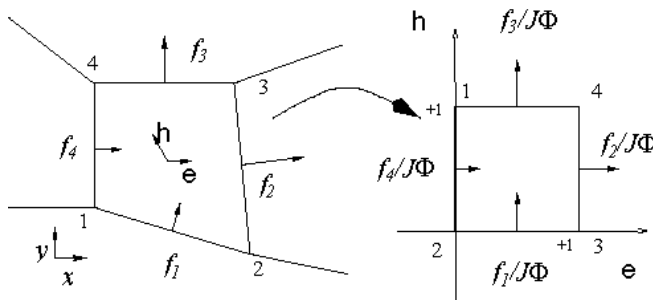
Figure 2: Non-orthogonal cells can be transformed using an isoparametric transformation. Pollock's method can then be applied to the resulting unit cell (from Prevost et al. 2001).

With Pollok's tracing algorithm, the natural extension of the 2D streamtube approaches of the 70's and 80's should be to define 3D streamtubes. But keeping track of geometrical objects in 3D is a cumbersome and numerically expensive proposition. A simpler and more efficient approach is to consider every streamline as the center of a streamtube who's volume is known—$\Delta V = Q_t \Delta \tau$, where Q_t is the total flow rate and $\Delta \tau$ is the delta TOF required to cross the gridblock—but the boundaries are not. Thus, streamlines with small TOFs are equivalent to streamtubes with small volumes, i.e. fast flow regions. Conversely, streamlines with large TOF are equivalent to streamtubes with large volumes, i.e. slower flow regions. Reformulating the transport problem along a streamline using TOF—rather than along a streamtube using volume—is the one key innovation that has allowed SL flow simulation to succeed for use in complex, 3D problems.

Figure 3: Filling a streamtube with a given volume is equivalent to walking the center streamline of the tube to a given time-of-flight (from Thiele et al., 1996).

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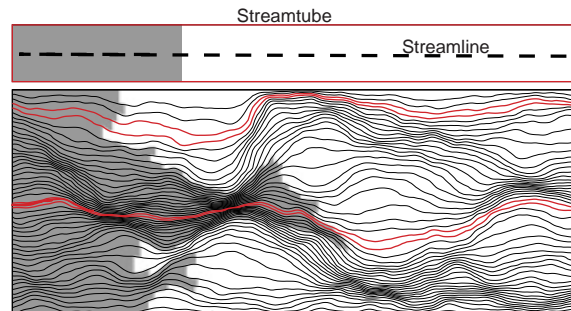
Key Idea #2: Recasting the mass conservation equations in terms of time-of-flight.

The understanding that using a TOF-variable along streamlines rather than a volume-variable along streamtubes came through the reformulation of the 3D mass conservation equations in terms of TOF. This was first shown by King et al. (1993) and later expanded on by Datta-Gupta and King (1995). The central assumption in the derivation was that the streamlines did not change over time—an assumption later relaxed as described in the next section. The derivation is simple (Blunt et al., 1996) and starts with knowledge of a one-dimensional conservation equation of a species i given by (the superscript 1 stands for 1D)

$$\frac{\partial M_i^1}{\partial t} + \frac{\partial F_i^1}{\partial x} = 0 \, .$$

The goal is to demonstrate that by combining one-dimensional solutions along streamlines it is possible to reproduce the 3D solution. In other words, that there is a vector v such that

$$\frac{\partial M_i}{\partial t} + \nabla \cdot F_i = 0 = u \frac{\partial M_i^1}{\partial t} + v \cdot \nabla F_i^1 \, .$$

By defining a coordinate ξ that is parallel to v (i.e. a streamline) it is possible to write that

$$v \cdot \nabla = |v| \frac{\partial}{\partial \xi} \, .$$

Now consider the definition of the TOF, which leads to the following expression

$$\tau = \int \frac{\phi}{|v|} d\xi \quad \rightarrow \quad \frac{\partial \tau}{\partial \xi} = \frac{\phi}{|v|} \quad \rightarrow \quad |v| \frac{\partial}{\partial \xi} \equiv v \cdot \nabla = \phi \frac{\partial}{\partial \tau}$$

and allows the three dimensional conservation equation to be re-written using a one-dimensional flux along a streamline as

$$\frac{u}{\phi} \frac{\partial M_i^1}{\partial t} + \frac{\partial F_i^1}{\partial \tau} = 0$$

There are a number of assumptions buried in this derivation. For example, that the flowrate along each streamline is incompressible ($\nabla \bullet v = 0$), that the streamlines do not change over time and that the 1D solutions must have the same boundary and initial conditions as the 3D problem. But the derivation shows that a three-dimensional transport problem can be re-written in terms multiple one-dimensional problems along streamlines. While this was known intuitively from the work on streamtubes, the TOF formulation offers a compelling mathematical framework. For the simple case of an incompressible waterflood it is thus possible to write

$$\phi \frac{\partial S_j}{\partial t} + \bar{u}_t \cdot \nabla f_j = 0 = \sum_{streamlines}^{all} \left(\frac{\partial S_j}{\partial t} + \frac{f_i}{\partial \tau} \right)$$

The most important detail about this equation is that the total velocity in the 3D problem has disappeared into the TOF of each individual streamline. It is this decoupling of a 3D heterogeneous

system into a series of 1D homogenous systems in terms of TOF that makes the SL method so attractive.

Key Idea #3: Periodic updating of streamlines.

The fixed streamtube assumption was probably the single most significant drawback that prevented a wider use of the technology during the 70's and 80's. Martin & Wegner (1979) and Renard (1990) did consider changing streamlines, but it was not until the mid 90's that the fixed-streamline assumption was relaxed for good (Thiele et al. 1996, Batycky et al. 1997). While the interest at the time was to account for changing streamlines because of the rapidly changing mobility field in miscible gas injection problems, the real application was for problems with changing well conditions and gravity.

The idea was to treat the problem as a succession of steady-states by considering each updated streamline field valid only for a fixed time interval before updating it. The method worked well for mobility induced nonlinear problems, but mapping analytical, self-similar hyperbolic solutions (Thiele et al. 1995, 1997) would not allow to solve systems with changing well conditions and gravity, due to requirement of uniform initial conditions along streamlines imposed by the analytical solutions. One additional element was needed: the ability to solve transport problems with generalized initial conditions along each streamlines (Batycky et al. 1997). Streamline geometries could then change at will, while guaranteeing that fluids would be transported in the correct direction by ensuring that inital compositions would be picked-up from the their position at the end of the previous timestep.
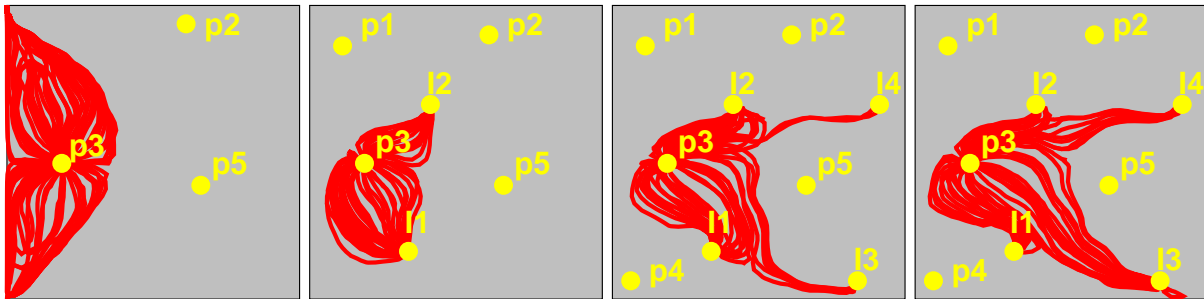
Figure 4: *Streamline geometries can change due to changing well conditions—i.e. rate changes, new wells coming online, or wells being shut-in—as well as a changing mobility field. Rate changes and new wells coming online will have a stronger impact on streamlines geometries that changes in the mobility field alone.*

Key Idea #4: Numerical solutions along streamlines

Numerical 1D solutions along streamlines were first introduced by Bommer & Schechter (1979) to solve a Uranium leaching problem. Ironically, in their case the streamlines were assumed fixed and the numerical solution was introduced because there was no analytical solution for the problem they were interested in. Batycky et al. (1997) now combined changing three-dimensional streamlines with a general, one-dimensional, numerical solution in TOF-space. This merging of ideas was instrumental in allowing streamline-based simulation to be used in real field cases, where streamlines would not only change due to mobility differences but also because of changing well conditions. With every new set of streamlines, the correct initial conditions could be mapped onto the streamlines—i.e. the conditions existing at the end of the previous timestep—and moved forward in time numerically. This allowed to move components correctly in 3D despite significant and radical changes in streamline geometries due to changing boundary conditions, as in the case for complete shut-ins of wells or new wells coming online. Using 1D numerical solutions also

made it possible to consider any 1D solution along streamlines, including complex compositional displacements (Thiele et al. 1997) or contaminant migration displacements (Crane et al. 2000).

Key Idea #5: Gravity.

Including gravity presented a problem. The total velocity vector (which defines a streamline) is the sum of the phase vectors, but the phase vectors are not parallel in the presence of gravity. A solution was presented by Bratvedt et al. (1996) using the concept of operator splitting, an idea that had found previous application in front tracking (Glimm et al. 1983, Bratvedt et al. 1992). The concept of operator splitting in this case is simple, and revolves around solving the material balance equations in two steps: first a "convective step" is taken along the streamlines which is then followed by a "gravity" step along gravity lines—lines parallel to the gravity vector *g*. In the gravity step fluids are simply segregated vertically according to their phase densities only. As an example, the simple conservation equation of incompressible, immiscible flow can be written as
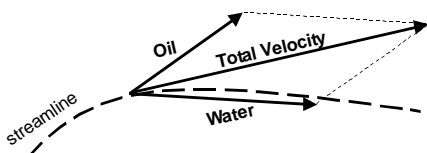
$$\frac{\partial S_j}{\partial t} + \frac{\partial f_j}{\partial \tau} + \frac{1}{\phi}\frac{\partial G_j(S_j)}{\partial z} = 0;$$

$$G_j(S_j) = f_j \sum_{i=1}^{n_p} \lambda_i (\rho_i - \rho_j); \quad f_j = \frac{|u_j|}{\sum |u_i|}$$

and is solved by splitting the conservation equation in two such that the solution of one becomes the initial conditions for the next.

$$\frac{\partial S_j}{\partial t} + \frac{\partial f_j}{\partial \tau} = 0; \quad \frac{\partial S_j}{\partial t} + \frac{1}{\phi}\frac{\partial G(S_j)}{\partial z} = 0$$

While the order of the solution is mathematically immaterial, streamline-based simulation always solves the convective step first followed by the gravity step.


Figure 5: In the presence of gravity, the phase velocity vectors are not aligned with the total velocity vector defining the streamline. Thus, moving components along the total velocity for multiphase flow will not account for gravity segregation. This is corrected using an operator splitting approach.

Key Idea #6: Compressible Flow

All streamtube and streamline work in the past was restricted to the assumption of incompressible flow. The reason, of course, is that incompressible flow introduces simplifying assumptions that are particularly suitable for SL simulation. Two assumptions in particular are worth mentioning: 1) source and sinks correspond to wells, meaning that all streamlines must start in a source (an injector) and end in a sink (producer); and 2) the flow rate along each streamline (or streamtube) is constant. The second assumption is particularly important as it implies that transport along a streamline only involves solving for the component wave speeds, with each phase velocity simply given by $q_j = q_t * f_j$. The problem, of course, is that there are no real systems that are incompressible: all real field cases involve compressible flow characteristics. PVT properties can be a strong function of pressure, as in black-oil systems, and the voidage replacement ratios (reservoir volume

in/reservoir volume out) can deviate significantly from unity, either locally or on a field basis leading to strong pressure changes.

In compressible flow, streamlines can start or end in any gridblock that act as a source or sink because of the compressible nature of the system, even if the block has no well. For example, in expansion type problems, any gridblock that sees its volume increase with decreasing pressure is a source and thus a potential starting point for a streamline. Figure 6 is a good example of this. It shows streamlines under primary depletion. Streamline now start in the far field and end in producers that act as sinks, yet there are no sources (injection wells) in the traditional sense. In reality, streamlines in Fig. 6 have multiple sources along each streamline, since every grid block a streamline passes through produces some fluid through expansion and thus acts as a source. As time increases and the pressure transient moves further out, the streamlines cover a larger area of the reservoir.
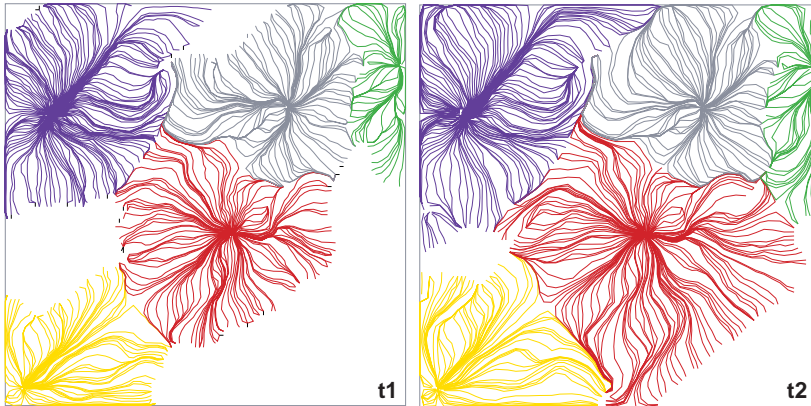

Figure 6: In compressible flow, gridblocks can act as sources even though there are no injections wells. In the case of primary depletion, a streamline will start in the far field and end in a producer and produce some volume from each gridblock it crosses.

Determining and tracing streamlines in compressible flow is not difficult. Pollock's tracing algorithm is valid regardless of how the flow velocities were determined. A significant extension to the mathematical formulation though is required to account for the coupling between saturations/compositions and pressure along the streamlines as well as accounting for a non-constant flow rate. One approach has been published by Ingebrigtsen et al (1999). A different, un-published approach has been implemented into a commercially available code (3DSL) and used for modeling compressible immiscible and miscible three-phase systems (Blackoil & Miscible Gas Injection). But while streamlines can model truly compressible systems, the inherent speed advantage over FD methods can diminish significantly depending on model size and governing displacement mechanisms. This is due simply to the constraint that if absolute pressure needs to be properly resolved properly to capture the transients, then limits on the global timestep size are very similar between FD methods and SL methods. There are, however, still examples where even compressible SL solutions are the only possible method to give an answer when modeling very large secondary and tertiary displacement processes.

If PVT properties are only a weak function of pressure, the incompressible framework can still be used successfully through the introduction of leaky boundaries. Leaky boundaries are distributed uniformly around he edges of the simulation model, and each boundary cell is allowed to inject or produce exactly the amount of volume so as to ensure a voidage replacement ratio of one as required by the incompressible formulation. The approach works remarkably well, with streamline from the leaky boundaries simply mimicking flow from the far field that would be observed in a closed but compressible system. Production profiles show similarly good comparison. The advantage with this approach is that historical injection/production volumes on a per well basis are honored exactly while the speed and efficiency of the incompressible formulation is retained.
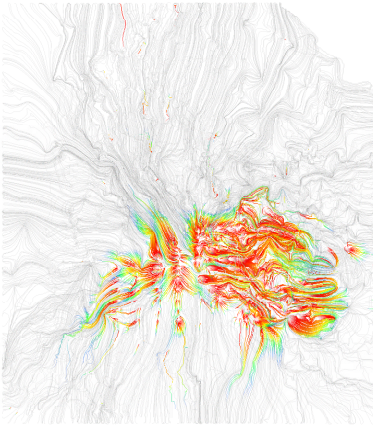
Figure 7*: The use of leaky boundaries allows to model systems with non-unit voidage replacement ratio and PVT properties that are a weak function of pressure in incompressible mode, while honoring historical injection/production well volumes.*

The previous six key ideas are central to the current state of SL simulation. Many mathematical details have been left out in the interest of time and clarity, but the curious reader will find many of the publications referenced to be excellent sources. For an outstanding, comprehensive source the reader is also referred to Batycky's PhD Thesis (1997).

WHY STREAMLINE-BASED SIMULATION IS SUCCESSFUL

Many papers in the last few years have clearly shown the applicability of SL simulation for solving problems that have traditionally been difficult to model with more conventional techniques: near incompressible displacements in large, heterogeneous earth models. Rather than re-iterating the many excellent examples and important conclusions already in the literature, the questions as to why streamline-based simulation has been so successful and has so quickly re-surfaced as a powerful alternative to more classical simulation techniques is addressed and where possible, illustrated through examples. This relevant question was also discussed by Baker et al. (2001).

Flow Visualization

The single most attractive feature for many engineers is the visual power of streamlines in outlining flow patterns. Rather than having to rely on a time-sequence of saturations changes, streamlines offer an immediate snapshot of the flow field clearly showing how wells, reservoir geometry, and reservoir heterogeneity interact to dictate where flow is coming from (injectors) and where flow is going to (producers). The ability to see the entire flow field at once is powerful and always yields surprising flow behavior. Real fields, even those drilled in regular patterns, rarely show streamlines conforming to the expected distribution of fluids. It is not unusual to see wells communicating with other wells far outside the expected pattern. While such behavior might be attributable to a "wrong" geological model or to an imbalance in the pattern, streamlines are unrivaled in the ability to point out such problems.

Full Field Modeling

A direct consequence of fields rarely having clear patterns also means that the practice of relying on sector models is misguided, since it is difficult to "carve" out a piece of the model that has no flux across the boundaries for all times. This problem is well known in the industry and the success of sector models strongly depends on getting the correct flux in-and-out of the sector boundaries, or trying to use a "border" around the proposed sector. The best approach, of course, is to model the entire field allowing for patterns to evolve to whatever is imposed by the interaction of well locations, well rates, reservoir architecture, and heterogeneity. But the ability to opt for a full-field model simulation requires an efficient simulation approach, both in terms of memory storage as

well as computation time. Full-field models can get notoriously big (in terms of number of cells), even when using a limited number of cells between wells. While streamline-based flow simulation makes some simplifying assumptions to achieve this efficiency, in most cases a full-field streamline model is still preferable to a sector model under traditional approaches, since the error introduced by choosing approximate sector boundaries can potentially be much larger and more significant than errors introduced by the streamline model itself.[*]

Figure 7: *Example of streamlines for a full field model (streamlines colored by injectors) showing that selecting a 'sector' is not always easy..*

Efficiency and Computational Speed

One advantage of SL simulation over more traditional approaches is its inherent computational efficiency. The efficiency, though, comes at a price: simplified flow physics, a non-conservative formulation, and other assumptions. Yet for many real problems, SL simulation allows for solutions not possible in any other way. From large, multi-million cell models with complex heterogeneity to simulations of hundreds of equiprobable realizations. Efficiency here is understood as both memory and computational efficiency. Memory efficiency is a result of two key aspects of the formulation:

(1) streamline-based simulation is an IMPES-type formulation and therefore involves only the implicit solution of pressure; and
(2) tracing of streamlines and solution of the relevant transport problem is done sequentially. Only one streamline is kept in memory at any given time.

Using efficient memory management of grid arrays and an efficient linear solver such as Algebraic Multigrid (Stüben 2000), it is possible to run models with approximately 0.37MB per 1000 active

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[*] An attractive solution is to use streamlines in deciding what a "good" approximation of a sector model might actually be, since streamlines are by definition no-flow boundaries. One problem to overcome though would be that the streamlines would have to be assumed fixed over the simulation of the sector model—something that is rarely the case in full field models as new wells coming on line or old wells being shut-in can cause significant changes in the flow field. Streamlines can also change due to changes in the mobility field or due to gravity. Looking to the future though, it is non inconceivable to have a hybrid simulator that might combine the best attributes of traditional gird-based techniques with streamlines. A sector model could be built by initially simply stating all the wells that are to be part of the model, streamlines calculated from a full-field model would then delineate the zone, a finite-difference simulation might solve the flow problem only in the sector over a particular time-interval (say until the next big time-event) at which time updated streamlines would be used to generate a new sector model and the finite-difference simulation would be continued on the new sector model. Non-trivial details remain: success of such an approach would center on being able to transfer appropriate initial conditions between successive sector models. From an abstract perspective though, it would not be much different than a fairly sophisticated but physically based domain-decomposition approach.

cells (Samier et al., 2001). Having 400MB of available RAM—which today is available on most PC's—means that it is possible to run models with 1 million active cells on relatively inexpensive computational platforms.

Efficiency in computational speed with a near-linear scaling of run times with the number of active cells, on the other hand, is achieved because:

  (1) The 1D transport problem along each streamline can be solved efficiently.
  (2) The number of streamlines increases linearly with the number of active cells.
  (3) Streamlines only need to be updated infrequently.

While streamlines change over time due to mobility changes, gravity, and changing boundary conditions, for many practical problems, grouping well events into yearly or semi-yearly intervals and assuming that the streamlines remain unchanged over that period is reasonable. Field simulations with 30 to 40 year histories are successfully and routinely simulated with 1-year time steps (Baker et al. 2001). In contrast to other simulation techniques, the size and number of the global time steps (frequency of streamline updates) is only a function of the physical process modeled and completely *independent* from the size and heterogeneity of the 3D model.
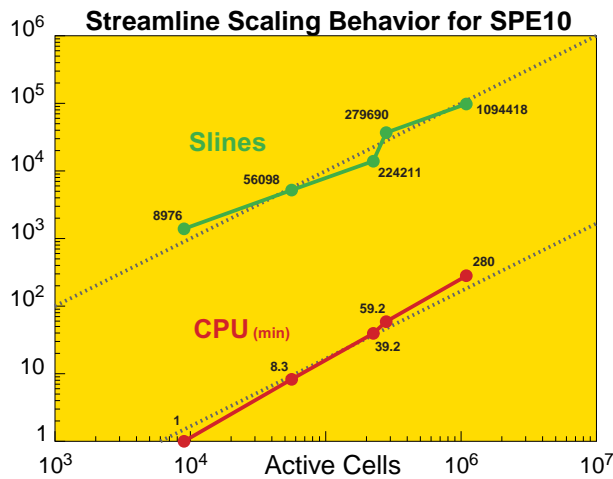
Figure 8: Example of linear scaling of run time and number of streamlines as a function of active cells for SPE Comparative Solution Project #10 using 3DSL, a commercial streamline simulator, on a PIII 866MHz PC.

Along each streamline, solution of the transport problem is particular efficient because it is constructed as a regularized 1D problem in TOF-space. Regularization of the 1D problem is very important. Keeping small cells along the streamline—resulting from streamlines flowing through very high flow regions near wells or cutting cell corners—would slow down the 1D transport solution along the streamline in much the same way as small cells tend to slow down IMPES solutions in regular simulators.

A good example to demonstrate the efficiency of SL simulation is Model 2 of the 10th SPE comparative solution project (Christie and Blunt, 2001). The total run time, T, of any streamline simulation is approximately proportional to

$$T \propto \sum_{1}^{n_{ts}} \left(t^{solver} + \sum_{1}^{n_{sl}} t_j^{sl} \right) \quad \text{where}$$

n_{ts} number of time steps (number of streamline updates)

t^{solver} time required to solve for the global pressure field ($Ax = b$) at each time step

n_{sl} number of streamlines at each time step

t_j^{sl} time to solve transport equation for each streamline

A near-linear scaling arises because:

1. The number of time steps (streamline updates) is independent of the model size, heterogeneity, and any other geometrical description of the 3D model. It is only a function of the number of well events and the actual displacement physics. For the SPE10 problem in Fig.8 all cases were run with the exact same number of streamline updates—24.
2. An efficient solver is expected to have a near-linear behavior as well (Stüben 2000).
3. The number of streamlines tend to increase linearly with the number of grid blocks all else being equal. Figure 8 illustrates this behavior.
4. The time to solve the transport problem along each streamline can be made efficient by regularizing the underlying TOF grid and choosing the number of nodes to use along each streamline regardless of the size of the underlying 3D grid.

The linear behavior with model size is the main reason why streamline simulation is so useful in the modeling of large systems. In FD's, finer models not only cause smaller timesteps due to smaller gridblocks but usually face problems because of increased heterogeneity as finer models tend to have wider permeability and porosity distributions. The usual workaround for traditional simulation techniques is to use an implicit or adaptive-implicit formulation, but for large problems these solutions can become prohibitively expensive, both in terms of CPU time and memory.

Flow Physics—Starting with the Simplest Model

There are significant assumptions buried in the formulation of SL simulation, particularly with regard to flow physics. This is because the technique grew out of an incompressible framework, with the main modeling interest being to capture flow resulting from reservoir architecture and heterogeneity interacting with injected and produced volumes—problems which traditional FD simulators are not well suited for, particularly as the models become large (number of cells) and more heterogeneous (larger property contrasts). From the beginning then, the focus for streamlines was on determining displacement efficiency, with run times increasing with increasing physics all else being equal. This is because physical complexity will tend to increase the number of required streamline updates (n_{ts}) and the time required to solve the 1D transport problem along each streamline (t_{sl}).

This favors investigating problems starting with the simplest and fastest model and progressively adding flow physics as required. A simulation study might, for example, start with inputting well locations, reservoir heterogeneity, reservoir architecture, and produced/injected volumes then assuming single phase, incompressible flow, progressing by allowing different phase relative permeabilities and phase viscosities (displacement efficiency), going further by including phase density differences (gravity), and finally considering compressibility and more complex phase behavior. This natural progression of adding physical complexity is possible in traditional simulators, but rarely used that way. Instead, the habit has become to include as much physical complexity as the simulator allows, i.e. starting with the most complex model first, then unraveling the contribution of each component—exactly the opposite of SL approaches.

Figure 9 shows an example of a real field that was in exploratory planning stages. The model size was 30x140x245 and streamlines quickly showed that gravity and vertical transmissibility barriers would be an important aspect in determining final recovery for the field. The runs also showed that a 3 phase model was required, though compressibility only seemed to have a second order effect. The ratio of run times for the various models was 1:4:7.3 (1Phase:3Phase:Blackoil). What is striking about this example is that an important conclusion about the flow behavior could be determined at the early geomodeling stage of the field, thus feeding back dynamic behavior of the model to the geoscientists.
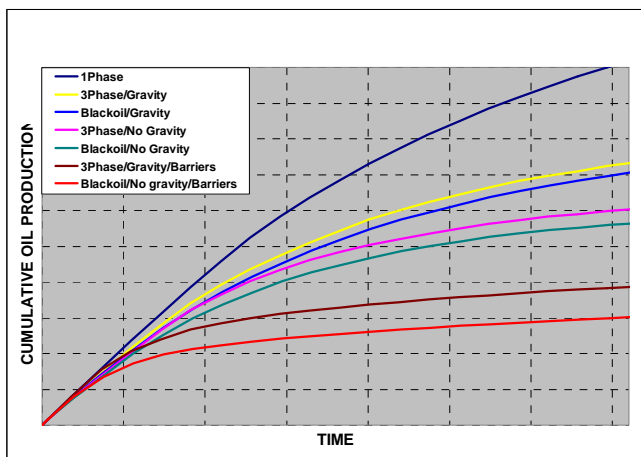
Figure 9: Streamlines offer rapid assessment of the impact of several first-order flow effects on displacement efficiency. For this particular example, gravity and 3-phase flow are important aspects of the model that would have been missed using a faster but simpler single-phase flow formulation.

Incompressibility and Well Controls

In truly incompressible systems, the absolute pressure level of the system is immaterial. All that is required is a pressure difference in order to calculate the total velocity using Darcy's Law. Though there are no real incompressible systems, the assumption of incompressibility is mathematically so powerful that it should be used whenever possible. For systems with strong water drives, systems having a voidage replacement ratio close to one, or systems that remain above bubble point, the assumption of incompressibility has been used with great success. These are all systems where streamlines work particularly well.

A very attractive consequence of incompressible systems is that historical well rates can be honored without having to previously ensure that the well models will give physical bottom-hole flowing pressures, i.e. P>0. This has important implications for history matching. Rather than starting the matching process by tuning well models to enforce historical volumes—in other words, trying to minimize the number of wells switching onto a pressure constraint—incompressible models allow the engineer to immediately begin matching the observed phase rates without regard to pressure. In fields where there are 100's, maybe 1000's of wells, it is practically impossible to honor historical well rates without allowing a good percentage of the wells to switch onto a bottom-hole-pressure constraint or even shut-in. Trying to fine-tune each well can be a painstakingly slow and costly exercise, which is made even more unnecessary in light of the fact that pressure might itself be of secondary importance. The ability to honor inter-pattern flow and generate novel, streamline-specific data (discussed further on), make history matching large, multi-well models a particularly well suited problem for SL simulation. The immediate consequence are overall better field and well matches obtained in significantly less time.

New Information

Streamlines go well beyond their visual appeal by producing new data not available with conventional simulators. This is possibly the most interesting and valuable contribution of streamlines to the area of reservoir simulation, though the industry has not yet settled on how to best use this information. Since streamlines start at a source and end in a sink, it is possible, for example, to determine which injectors (or part of an aquifer) are supporting a particular producer, and exactly by how much. A high watercut in a producing well can therefore be traced back to specific injection wells or boundaries with water influx. Conversely, it is possible to determine just how much volume from a particular injection well is contributing to the producers it is supporting—particularly valuable information when trying to balance patterns.

Streamlines also allow identifying the reservoir volume associated with any source or sink in the systems, since any block traversed by a streamline attached to a particular well will belong to its

drainage volume. For the first time, it is possible to divide the reservoir into dynamically defined drainage zones attached to wells. All properties normally associated with reservoir volumes can now be expressed on a per-well basis, such as oil in place, water in place, and average pressure, just to mention a few. This data was not previously available and so there is little in the literature as to how to exploit it. One immediate use though is apparent: determining displacement and production "efficiency" on a well-by-well basis. This topic is covered in more detail in a separate section, but is surely one of the reasons for the keen interest currently existing for SL simulation.
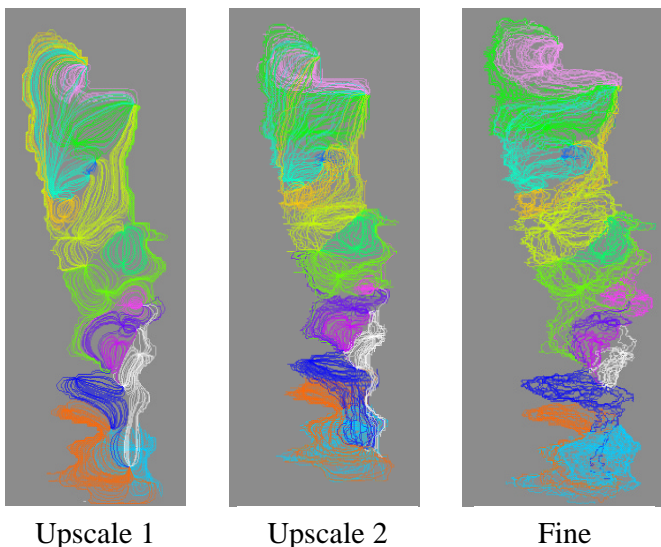
UPSCALING AND STREAMLINES

Three SL features seem to be particularly interesting for upscaling:

1. Producing fine-scale reference solutions (Samier et al., 2001).
2. Derive upscaled grid properties using streamlines (Christie and Clifford, 1997).
3. Lump cells using streamlines (Castellini et al. 2000, Portella and Hewett, 2000).

There are extensive variations on these themes in the literature and are not repeated here. The reader in encouraged to review the many excellent papers. In general, contributions can be separated into the application of streamlines as they pertain to validating upscaling methodologies and application of streamlines as they pertain to actually generating average, upscaled properties.
In the area of validation, recent work by Samier et al. (2001) suggest that streamlines might offer an additional feature beyond simply generating fine-scale reference solutions against which to check upscaled solutions.
The premise is that for upscaled system to have similar dynamic behavior as the original fine-scale model, wells should be draining similar volumes and those volumes should be connected in a similar way. Streamlines provide just that information. Comparing connected volumes over time for individual wells would offer a completely new way to analyze the relative performance of upscaling algorithms. Figure 10 and Fig. 11 illustrate this idea using an example from Samier et al.(2001). Figure 10 shows that the streamline patterns of the upscaled models reproduce the fine-scale streamlines only in certain parts of the field. Figure 11 quantifies this discrepancy and compares it to the fractional flow behavior of the well. Well P2C is a good example where matching the well porevolume over time also leads to a good match of the water fractional flow. Well P3, on the other hand, has no match of the fine-scale pore volume, but the fractional flow is acceptable.

Upscale 1   Upscale 2   Fine

Figure 10: Streamlines colored by producers for two upscaled model and the reference fine-scale model. Good upscaling should produce similar streamlines patterns and volumes associated with individual wells between the fine-scale model and the upscaled models (from Samier et al. 2001).
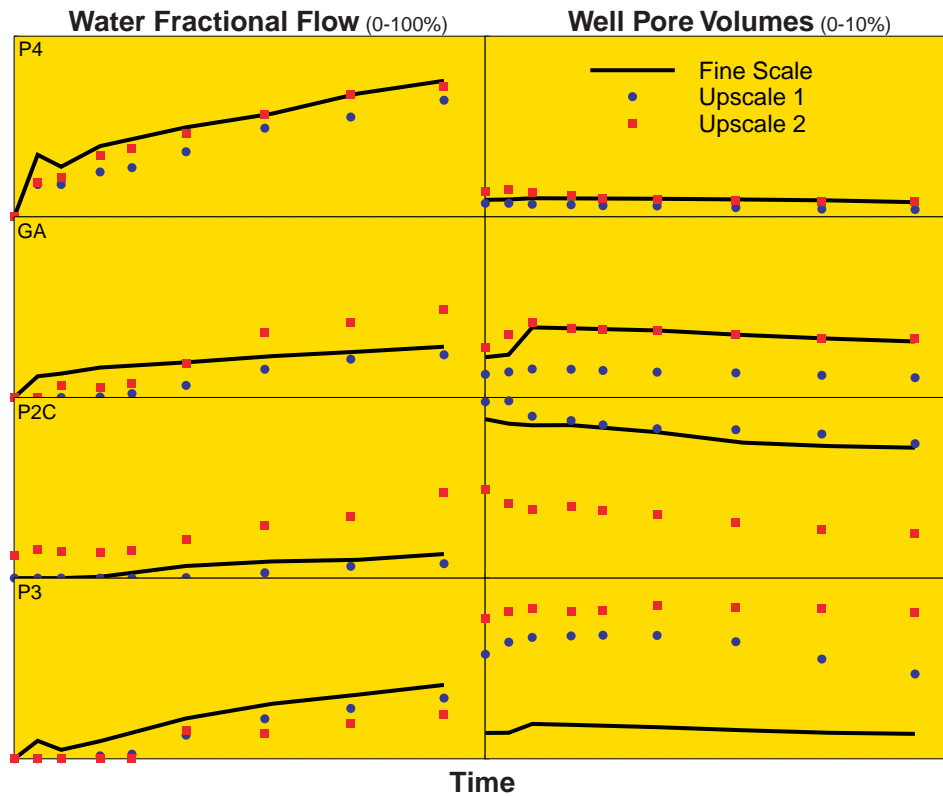
Figure 11: *Streamlines allow to compare volume associated with wells between fine-scale and coarse-scale problems. Wells having good agreement on pore volume between fine-scale and coarse scale are likely to give better matches.*

An upscaling analysis based on well volumes and geometry might, in the end, be more relevant than simply comparing production profiles. For real field cases, it is well known that upscaling can completely eliminate smaller faults, transmissibility barriers, and other geometrical features so as to significantly change the flow pattern and drainage volume of a well. In such cases, there is no tweaking of flow parameters (such as relative permeability) that can remedy this problem, though a match with unphysical flow parameters might still be possible. The problem is geometrical, and until the flow patterns in the upscaled model are not adequately matched to what is seen in the fine-scale model it is of little use to pursue approaches based on other parameters.

HISTORY MATCHING AND STREAMLINES

One of the most promising applications of streamlines is in the area of history matching. Because streamlines are tied to wells and at the same time delineate areas of the reservoir, the presumption is that there must be information hidden along streamlines that should help in the history matching process. This is indeed the case. Additionally, history matching reservoir behavior is a nonlinear[*] process requiring many forward simulations; having an efficient and fast method to generate many forward solutions is of great benefit. But aside from exploiting the speed of SL simulation, streamlines have been used in three other ways for history matching:

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[*] The term *nonlinear* in reservoir simulation refers to the fact that the coefficients of the governing PDE's are themselves functions of the independent variables (pressure, saturations and/or compositions). In practical terms this means that the flow field—and thus the streamlines—change over time. Streamlines also change because of changing well conditions over time. Any realistic attempt to match historical production data by modifying the underlying 3D geological model must account for this fact. Assuming only one set of streamlines is equivalent to solving a linearized version of the flow equations and assuming that wells never change operating conditions over the life of the field.

1. Analytical derivation of sensitivity coefficients which are then used to set-up an inverse problem (Wen et al. 1998, Vasco et al. 1999);
2. Defining average reservoir regions associated with wells and the subsequent changing of grid properties that way (Emanuel and Milliken 1997,1998);
3. Modify grid properties traversed by streamlines so as to slow or increase flow along these streamlines (Wang and Kovscek 2000; Caers et al. 2001, Agarwal and Blunt, 2001).

Deriving analytical sensitivity coefficient from streamlines is an efficient approach but assumes fixed streamline paths for all time (a linear model). Furthermore, there remains the problem of the solution of the inverse problem. Since streamlines are usually used in the context of large fields with many wells—i.e. those fields that are too computationally intensive for FD's—there remains a significant bottleneck in trying to solve such a large inverse problem.

More complementary to SL simulation are methods that attempt to use streamlines to directly modify gridblocks associated with wells that are not matching. Avoiding the direct solution of an inverse problem, leaves the door open for history matching fields at a finer, geologically more realistic scale. Two methods stand out: the AHM approach of Emanuel and Milliken (1997,1998), and the work by Wang and Kovscek (2000) and extensions thereof (Agarwal and Blunt, 2001; Caers et al. 2001).

The AHM approach of Emanuel and Milliken (1997,1998) has been applied with impressive success on a number of real fields. Its most distinguishing feature is that it does not rely on any mathematical algorithm to attempt convergence, and is much closer to traditional history matching forcing the engineer to use judgment and experience to modify model parameters. In the usual manner, the updated model is re-run and checked against field performance. The process is continued until an 'acceptable' match is achieved.

The basic premise of AHM is that a good match can be achieved by altering geological grid properties—permeability, porosity, net-to-gross ratio—associated with wells. Since streamlines allow to naturally define zones associated with wells, it is possible to implement such an algorithm only using information from streamlines. It is not possible to implement the AHM using FD's. Once zones associated with individual wells are identified, the statistics (but not the spatial structure) can be changed as guided by experience and understanding of the particular reservoir. Emanuel and Milliken (1997,1998) have identified several statistics that can be modified, the
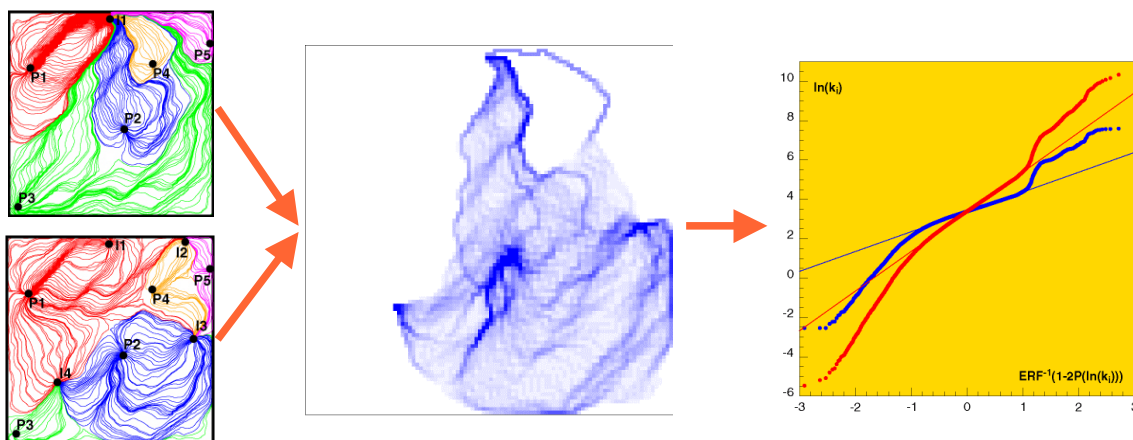

Figure 12: In the AHM approach streamlines are used to define average well zones, and wells are history matched by changing the statistics of the field—such as the Dysktra-Parson coefficient—but without attempting to change the spatial structures of the field.

Dykstra-Parsons coefficient probably being the most important one. Figure 12 is a schematic of the approach: streamlines, possibly at different times, are used to define an average zone of the reservoir associated with a particular well. In Figure 12 the average zone is for well P2. Once the average well zone is defined, grid properties for that zone can be manipulated to yield a better history match. Important details remain. The AHM will not converge from a "disastrous" initial guess of the geological model—the premise is that a reasonable geological model does exists and that convergence can be achieved through sound reservoir engineering understanding of the process. All real fields will have changing well conditions, so that either an average zone has to be defined (as in Fig. 12) or there has to be lumping of well events.

In a similar fashion as the AHM method, the approach of Wang and Kovscek (2000) tries to modify grid properties using information provided by streamlines. The basic idea here is to relate the fractional-flow curve at a producer to the water breakthrough of individual streamlines. By adjusting the effective permeability along the streamlines, the breakthrough time of each streamline necessary to reproduces the reference fractional-flow is found. The drawback is that the theory is based on fixed streamlines with no gravity, although recent work by Agarwal and Blunt (2001) extended the approach to compressible systems with gravity. Recent developments (Caers et al. 2001) have also shown very promising results in extending the method by using a Gauss-Markov random function constraint to translate effective permeability perturbations returned by the streamlines into modified permeability maps that honor a target histogram and variogram. Figure 13 shows a schematic of the approach. Including the Gauss-Markov random function constraint produces permeability fields (Fig. 13 bottom left) that can match the fractional flow function at the producing while eliminating the unrealistic "look" of matched fields using streamlines alone (Fig. 13 bottom right).

The method is appealing, because as in the AHM there is no inverse problem to solve, yet the original spatial description of the geological field is maintained while matching well behavior. Though the methodology has only be shown on a very simple synthetic, 2D case with fixed streamlines, the potential of combining streamline-derived information and geostatistical algorithms for constraining reservoir models is significant.
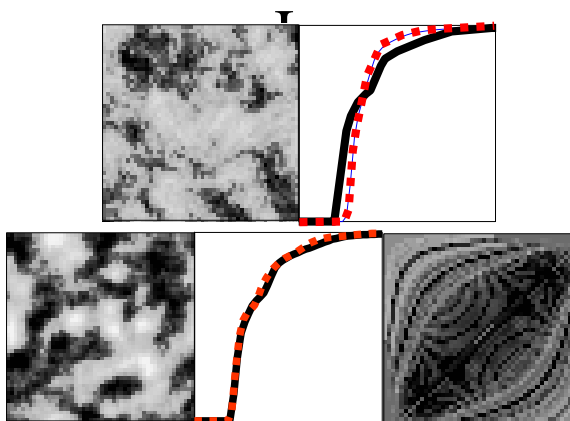

Figure 13: Changing properties along streamlines to yield a history match can lead to unrealistic looking permeability fields (bottom right). Using a geostatistical constraint when reintroducing effective properties derived from streamlines produces fields honoring the original spatial constraint (bottom left) as the original field (top left) (from Caers et al. 2001)

WELL ALLOCATION FACTORS & POREVOLUMES

One of the more exciting applications of streamlines stems from the novel information provided by the streamlines themselves: a) well allocation factors and b) well pore volumes. Well allocation factors quantify the amount of flow in a particular well due to other wells in the system. Well pore volumes are the reservoir volumes associated with each individual well. How can this information then be used to optimize field performance?

Pattern Balancing.   Knowing the allocation of flow between well pairs is the starting point of any technique to balance well patterns in waterfloods. Traditionally, allocation numbers have been

determined using empirical methodologies—some more sophisticated than others—but empirical nonetheless. Streamlines offer an immediate and rigorous solution to this problem: for each injector, the amount of injected fluid supporting any producer in the field is known exactly, and therefore the allocation of fluid between injectors and producers in a pattern is obtained automatically as part of any simulation. This also means that streamlines can immediately point out any fluid loss to wells outside a pattern—a potentially serious problem—and something empirical methodologies will always severely underestimate. All simulations performed by the author on real fields have always yielded unexpected patterns with injector-producer connections well outside what one might consider the intuitive well pattern.
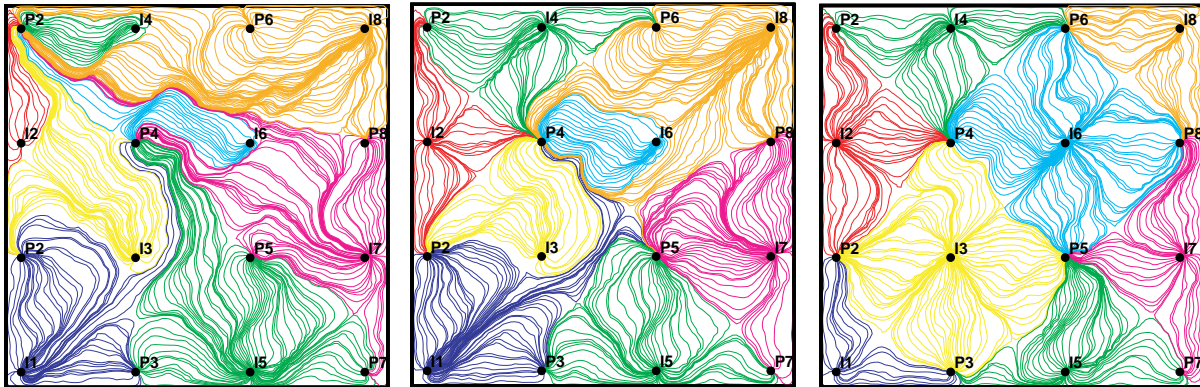
Figure 14: Streamlines automatically allow to determine the allocation of flow between wells by summing the flux of all streamlines associated with a particular well, well pair, or group of wells. Using this information and the visual display of streamlines allows patterns to be balanced more correctly and efficiently than with current techniques. From left to right: rates are progressively changed to yield a balanced pattern.

Injector Efficiency   But do streamlines offer any radical new insights to help the reservoir engineer optimize field performance? Can the visual appeal and underlying data of streamlines be translated into meaningful, new cross-plots? The answer is yes, and as streamlines become more widely used additional applications will certainly emerge.

An important component in optimizing field performance is to be able to compare and rank the efficiency of injectors. More "efficient" injectors, for example, should probably receive a higher portion of available injection water than the less efficient injectors. Failure of a waterline might reduce the amount of water available to a number of injectors forcing some to be closed—knowledge of the efficiency of the injectors is invaluable in such circumstances. While there might be different ways to determine the efficiency of an injector, one must be the amount of offset oil produced as a function of volume injected. This is exactly the type of information streamlines provide naturally. Figure 15 shows real data for a mature waterflood. Cross-plotting volume injected with offset oil produced for each injector gives a powerful snapshot of the efficiency of the injectors over the entire field. By picking a cutoff percentage of oil produced to water injected (10% in this example), the cross-plot can be divided into four quadrants—here labeled 1,2,3, and 4.
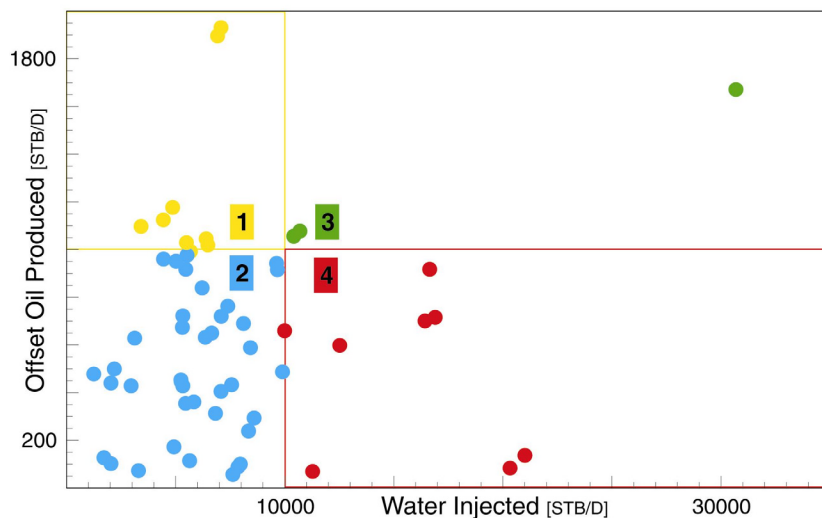
Figure 15: Streamlines allow to cross-plot injected water rate with offset oil production caused by that water for each injection well. This allows to immediately identify less efficient injectors (red), efficient injectors (yellow), and injectors in-between (blue and green). In this case the four quadrants were created using an arbitrary 10% efficiency cutoff.

Quadrant 1 (yellow) represents the most efficient injectors, i.e. those injectors that produce the most amount of oil for every barrel of water injected. Quadrant 4 (red), on the other hand, includes the most inefficient wells—wells that inject high volumes of water but produce little in terms of offset oil. These wells are prime candidates for shut-in, particularly in cases where the amount of water is limited or could possibly be used more efficiently elsewhere in the field. Finally, quadrants 2 and 3 represent intermediate cases. Quadrant 3 wells produce less than 10% injected volumes, but are significant in absolute terms and are therefore good candidates for closer analysis. Similarly, quadrant 2 wells produce less than 10% of injected volume, but on the other hand do not require large injected volumes. What emerges is an invaluable reservoir engineering analysis: can water used by quadrant 4 wells (and possibly water from north-east wells in quadrant 3) be redirected to quadrant 2 and 3 wells to push them into quadrant 1? Figure 15 is a roadmap for the reservoir engineer trying to optimize field performance or facing day-to-day operational decisions as to where to inject limited amounts of water. Such data has never before been available in this manner and with this precision.

If streamlines can help quantify the efficiency of injectors, what information might be available for producers? The fractional flow of a well is already an efficiency indicator—a well with a high fractional flow is less efficient than one with a low fractional flow. But since streamlines allow to determine the pore volume associated with any well, a significantly more powerful analysis might be to cross-plot oil production versus average oil saturation (or even movable surface oil volumes) for each producer. Such a plot would immediately identify efficient producers—those producing at high rates while contacting relatively low oil saturations. Similarly, inefficient producers would be wells producing at low rates while contacting high average oil saturations. Figure 16 is an attempt at such a cross-plot for the same real field as in Figure 15. Here the cross-plot is divided using diagonal lines, with the yellow line representing the most efficient linear relationship between oil rate and average oil saturation for this particular field. There are three wells that define this line. The green and red lines are then drawn parallel to the yellow line. Using a cut-off oil rate then generates natural sub-areas of the cross-plot clearly identifying the most efficient producers (yellow), the most inefficient (red), and wells that might have potential for improvement through workovers or sidetracking. Wells in black fall somewhere in between, being rather inefficient in terms of production but contacting a significant average oil saturation.
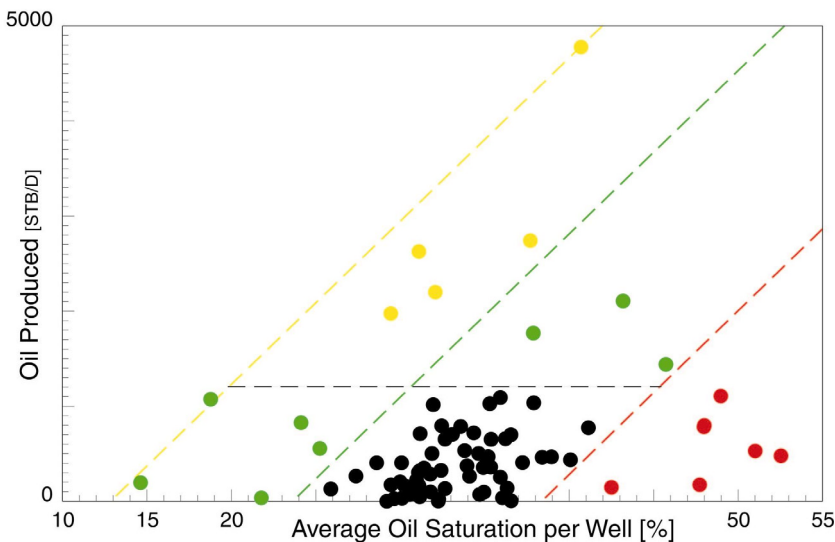
Figure 16*: Streamlines allow to determine the drainage volume of a well thereby allowing to determine the efficiency of producers through a cross-plot of oil rate vs. average contacted oil saturation (or movable surface oil volume) per producer.*

RANKING

When streamlines re-appeared in the early nineties, the profound impact geological models could have on the quality of simulation results was generally understood. The proliferation of sophisticated algorithms to model structure, faults, and properties is a testament to that. One of the earliest applications perfectly tailored for low-physics, high-speed, SL simulations was the ranking of fine-scale geological models—models that were clearly too large for traditional approaches but which needed ranking beyond usual static variables such as hydrocarbon pore volume or connected volumes. Surprisingly, ranking has not emerged as one of the key applications of streamlines. Why?

Fine-scale geological models are usually constructed by geoscientists—upstream from the reservoir engineer—and in many cases using little or no dynamic data. Streamlines seemed attractive because the low-physics aspect of the formulation appeared to open the doors to simulation to the geoscientist not trained in that area. Unfortunately, it has not turned out this way. The reality is that dynamic ranking of geological models is a strong function of the flow-physics. Figure 9 is a good example of this: recovery of the single-phase flow model is significantly higher than the 3-phase flow model, and gravity plays an important role in increasing recovery. It is not surprising then, that single-phase flow will yield very different ranks compared to more complex flow simulations, such as waterflooding, miscible gas injection, or compositional problems. Most importantly, single phase flow physics is usually not rank-preserving with respect to more complex flow physics, as is illustrated in Fig. 17 below. Truly relevant ranking studies of fine-scale geomodels require as much knowledge of reservoir engineering and dynamic flow simulation as upscaling and history matching might. In the case of streamlines, accounting for gravity, changing streamlines, and fractional flow effects are fundamental to any ranking study.

The problem of the interaction of ranking and complex flow physics can be demonstrated with a simple, 3D five-spot pattern (Thiele and Batycky, 2001). Figure 17 shows 30 equi-probable realizations in which the rank determined by TOF—linear, single phase flow where the TOF of the fastest streamline is taken as a cutoff for all other streamlines and all pore volume with TOF's less than the cutoff is then used to rank the models—versus the recovery at breakthrough with increasing complexity of displacement physics. Figure 17 shows how quickly the ranking can change. Picking a P_{10}, P_{50}, and P_{90} based on TOF ranking is not a good indicator of how recovery for a more complex displacement might behave.
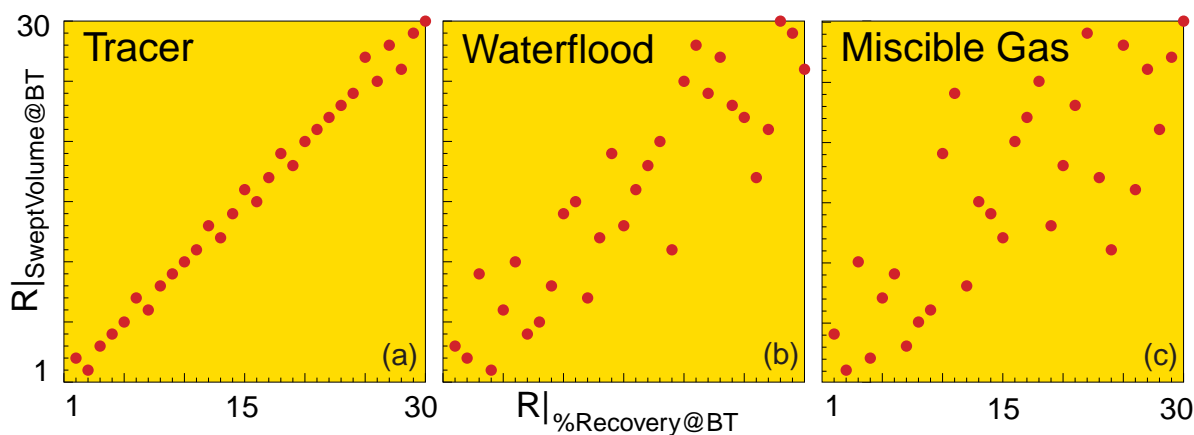
Figure 17: *Flow physics can significantly change the ranking behavior of systems of equi-probable geological models. Here, 30 realizations are cross-plotted using the TOF-rank with the rank obtained using recovery at breakthrough with progressively more physics (from Thiele and Batycky, 2001).*

A more likely application of streamlines will be that of ranking a number of smaller child models derived from a single large earth model. In size, the child models will be smaller than the original geological model but still significantly larger than the ultimate simulation model that might be used in a more conventional flow simulator. In absolute terms, the child models might be on the order of 250 to 500 thousand active cells. It is easy to see how just considering a few parameters can increase the number of child models derived from a single large geo-parent: three upscaling methods times two sets of relative permeabilities times five fault models already gives 30 child models. The number is easily increased into the 100's by considering just a few more parameters.

THE FUTURE OF STREAMLINE SIMULATION

Modern SL simulation is a powerful and complementary tool to traditional techniques used in engineering the upstream exploration and production of hydrocarbons. As a whole, the industry is still exploring the most optimal use of this technology and how it might be efficiently integrated into the current work flows used by individual companies. The next few years will bring a further maturing and extended application of the technology. It is not unreasonable to expect that most all companies using conventional simulation technology today will in one form or another use SL simulation in their work. What remains largely unknown is if new users groups, such as geologists and geophysicists, will adopt the technology in order to bring a dynamic flow component to their analysis. What then might be expected over the next few years in terms of developments?

Compositional Simulation

The revival of modern SL simulation in the early 90's centered in part on miscible gas injection and as an alternative to the difficulties conventional methods had in resolving highly nonlinear, multiphase displacements through heterogeneous reservoirs.   The numerical difficulties encountered by conventional methods for such problems continue to persist and remain a serious problem in many field-scale compositional studies. The only solution is usually to reduce the number of cells and/or reduce the geological complexity directly affecting the numerical performance.   Representing the phase behavior via a more manageable number of pseudo components is the other alternative. In most cases, a combination of the two is used. But the price for these shortcuts is high. Numerical artifacts can become so severe as to completely mask any possibly beneficial phase behavior effects that might have been the reason for the numerical simulation in the first place. And going to more powerful hardware might not always yield the

expected results, since run times for traditional simulation techniques can scale with a power of two or higher, quickly turning simulations into month-long computational marathons.

Streamlines remain unrivaled in the ability to efficiently transport components along flow paths, even in the presence of extreme permeability/porosity values. In the very specific case of multicomponent, multiphase flow where complex phase behavior is critical, the decoupling of the three-dimensional solution into a series of one-dimensional solutions is so attractive as a way to control numerical dispersion that it cannot be overlooked (Thiele et al., 1997). For large fields under gas injection, streamlines offer advantages that will unlikely be matched by traditional technologies: the ability to model full-field scenarios with reasonable inter-well spatial resolution in acceptable run times on affordable platforms.
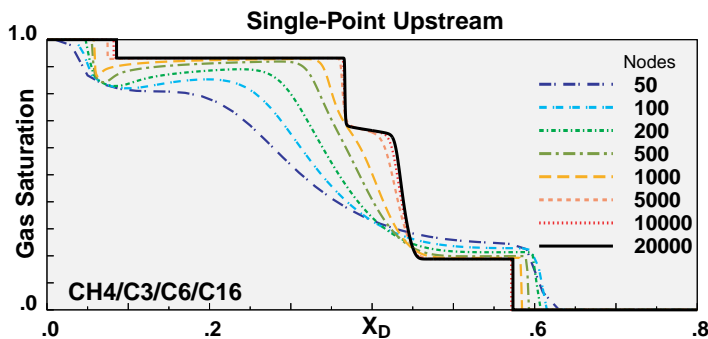
Figure 18: Four-component displacement showing that numerical diffusion remains a serious problem for field-scale reservoir simulation, where the number of gridblocks between wells is often significantly less than 50 (blue line). From Thiele & Edwards (2001).

Tracing Streamline Through Structurally Complex Reservoirs

Tracing of streamlines currently rests on Pollock's bilinear interpolation, which in turn makes the fundamental assumption that there is a single velocity per cell face. Structurally complex reservoirs, on the other hand, often require multiple connections across a single face, as might be the case in the presence of faults. This adds a layer of complexity to the tracing algorithm, since cells might now have multiple velocities across a single face, theoretically even in opposite directions. The streamline paths in a cell must now be traced through sub-cells—the geometries of which are dictated by the velocity vectors on each face—and to which Pollock's algorithm can be applied. This will give SL simulation the ability to model flow through heavily faulted and structurally complex systems while retaining much of its simplicity and speed. This will be an important extension to the technology and will likely allow its use for systems where traditionally more sophisticated meshing algorithm were used (such as finite-element or PEPI-grids). On-going research in this area should yield promising results within the next few years.

Streamlines in Fractured Systems

Streamlines have so far been primarily used in the context of single porosity systems, although intuitively fractured systems might seem suitable for streamlines since the fracture network can been interpreted as a fast flow conduit. But this does not address the matrix-fracture transfer, the main mechanism for production from fractured systems. Combining SL simulation with transfer functions—in essence source terms along each streamline—might make an extension to dual porosity systems possible. An important and necessary extension might also be the inclusion of capillary pressure, a mechanism not modeled in current streamline applications due to its diffusive behavior (capillary pressure acts in both directions, along and across streamlines, and therefore does not naturally lend itself to SL simulation). Such extensions are currently under review by several research groups and should yield an entire new range of applications for SL simulation if successful.

Parallel Simulation and Simulation of Very Large System

Computationally, streamlines are processed serially and completely independent of each other. This, of course, lends itself perfectly to parallelization. On a multiprocessor machine or cluster of machines, the transport problem along each streamline can be computed in parallel, thereby allowing significant speed-ups. Parallelization is required for the solution of very large systems (SVLS), systems that might be on the order of 10^7 or higher. Such systems are easily created in the case of giant oil fields (as might exist in the Middle East or Alaska) by simply allowing a reasonable block resolution between wells—25 grid blocks or more—and modeling the entire field without resorting to sector models. Even smaller reservoirs routinely have geomodels in range of 5 to 10 million cells. Large investments, both in terms hardware and software, have been made for the solution of such problems because it has been recognized that modeling the full field is critical for the engineering of optimal production scenarios. Streamlines are likely to play an important role in the future for tackling such difficult problems, particularly in assessing and screening potential scenarios for such giant models fields before resorting to more traditional approaches to confirm and cross-check a subset of the solution space.

The Future Simulator

Reservoir simulation is a complex field and in most instances requires expert knowledge to obtain meaningful results. Graphical user interfaces and workflows help users along and provide guidance by shielding users from some of the complexities involved. Useful and efficient visualization of results are essential in the interpretation and validation of results. But it is a reality that the vast majority of users employ reservoir simulators as a black-box—as a transfer functions that takes a proposed reality and projects it into the future. There is little time to gain a deeper understanding of the solutions and how these are obtained. What is really desired are quick answers that can be obtained relatively easy. For the simulator of the future this means that it should not be limited to a single approach: it should ideally choose which simulation technique might be appropriate at what time domain and act accordingly—all in the interest in delivering an answer that is as correct as possible in an as acceptable time as possible with as little effort as possible. Intelligent simulators—i.e. simulators that will automatically choose the most "efficient" solution technique for the problem at hand—will likely be the focus of future development in reservoir simulation.

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