Reservoir Surveillance of Mature Floods Using Streamline-based Workflows

Streamsim Technologies, Inc.
Oct 2014
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Poll Question

What geographic region are you from?

- North America
- South America
- Africa
- Middle East
- Europe
- Asia
- Other

Poll Question

What is your job title?

- Reservoir Engineer
- Exploitation Engineer
- Production Engineer
- Geologist
- Consultant
- Educator
- Student

Poll Question

What is your level of experience with reservoir simulation?

- I know nothing about it.
- I use it as a black box.
- I consider myself an expert.

Outline

- Objectives of Surveillance
- Classic Reservoir Surveillance Method
- Introduction to Streamlines
- Reservoir Surveillance with Streamline-based Metrics
- Flood Management via Well Rate Targets
- Case Study
- Conclusions

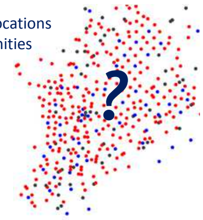
Objectives of Surveillance

- "The primary function of surveillance work is to assure that every project is operated in an effective manner in order to optimize recoveries and profit." by W.R. Lancaster – 1980.
- From G.C. Thakur JPT Oct 1991, waterflood surveillance includes:
  - Accurate reservoir description
  - Reservoir performance (field, pattern, well diagnostics)
  - Wells monitoring (rates, pressures, fluid profiles)
  - Water quality
  - Performance of surface facilities
  - Monthly comparison of actual vs. predicted behavior
  - Reservoir management information system (data gathering)
  - Diagnosis of problems and their solutions
  - Economic surveillance
  - Teamwork

Objectives of Surveillance

With large mature floods, how do engineers easily optimize recoveries and profits? Translates into identifying:

- Injector patterns
- Efficient use of injected fluids
- Fluid cycling
- Well rate targets
- Infill/conversion locations
- EOR/IOR opportunities



Engineering toolbox:

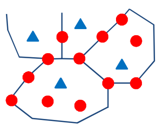
- Analogs
- Decline analysis
- Material balance
- Capacitance-resistance models
- Streamline models
- Numerical simulation

Introduction – What is Reservoir Surveillance?

- Reservoir surveillance is the association of produced volumes with injected volumes to identify:
  - well-pairs, patterns
  - pattern recovery
  - well rate targets
  - trends in production/injection data
- The key issue is: How are well-pairs identified and how are produced volumes associated with injected volumes?
  - Classic method -> define by hand
  - Streamline method -> based on flow response

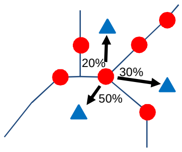
Classic Surveillance Method

- Define fixed patterns based on well locations.
- Well-pairs are <u>implied</u> from the pattern boundaries defined.
- Used for:
  - Injection vs production ratio (VRR) of pattern.
  - Estimate influx or efflux from pattern based on VRR.



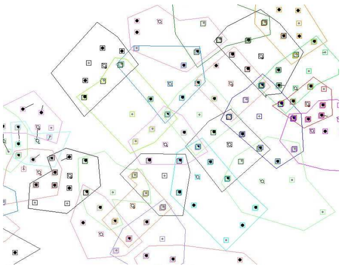
Classic Surveillance Method

- Allocate production back to each injector the producer is assigned to, via geometric well allocation factors (geo-WAF's)
- WAF's are assumed to be independent of flow rate, usually fixed through time.



Field A – Classic Surveillance

- Draw boxes by hand…
- 32 fixed injector centered patterns.
- Calculated geometric WAF's.



Limits of Classic Surveillance

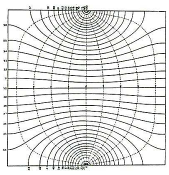
- Defining patterns is done by hand, time intensive, is non-unique.
- Results are heavily dependent on how the patterns are drawn and the WAF's.
- Pattern VRR is <u>implied</u> by the WAF values assigned.
- We know WAF's are neither fixed through time, or a function of geometry.

Reservoir flow is more complex, and off-pattern flow more common, then is assumed with classic surveillance.

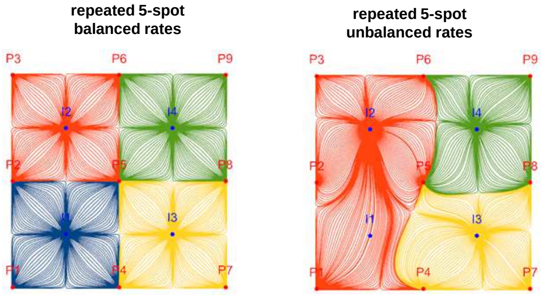
Overview of Streamline Simulation

What is a Streamline?

- A line that is tangential to the local velocity vector. Velocity vector follows local pressure gradient→Darcy's Law.
- Streamlines start at sources (injectors) and end at sinks (producers).
- Streamlines in *RE* since Lee 1946, Muskat 1948…



Analytical Streamline Paths

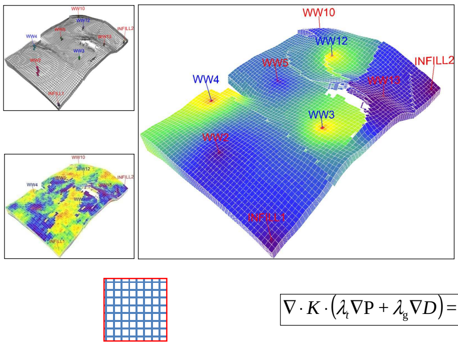


Streamlines colored by originating injector

Advances in Streamline Simulation to Field Scale Applications

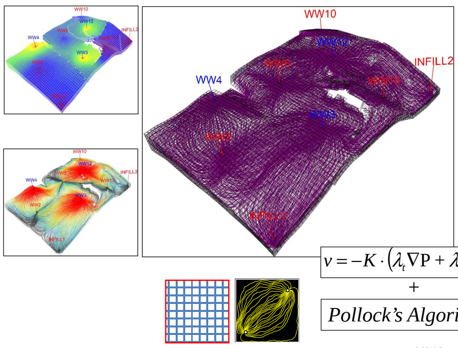
- Streamline developments post 1990…
  - Extension to 3D waterflooding (SPE 19805-PA, 27834-PA, 30758-PA, 36726-PA, …)
  - Extension to advanced displacements (SPE 38889, 77379, 84036, 132774-PA, …)
  - Reference books (Datta-Gupta & King 2007, Thiele et al. 2011)
- Modern streamline simulators are numerical.

Solve for Pressure



$$\nabla \cdot K \cdot (\lambda_t \nabla P + \lambda_g \nabla D) = q$$

Trace Streamlines

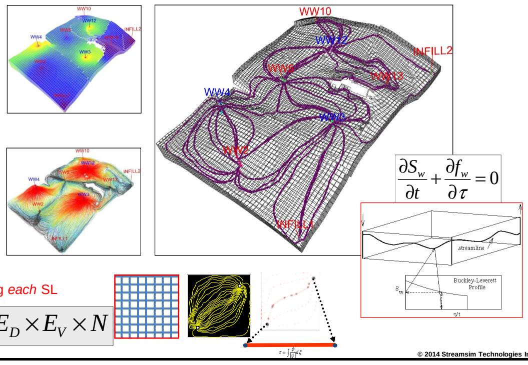


$$v = -K \cdot (\lambda_t \nabla P + \lambda_g \nabla D)$$

+

Pollock's Algorithm

Transport along Streamlines

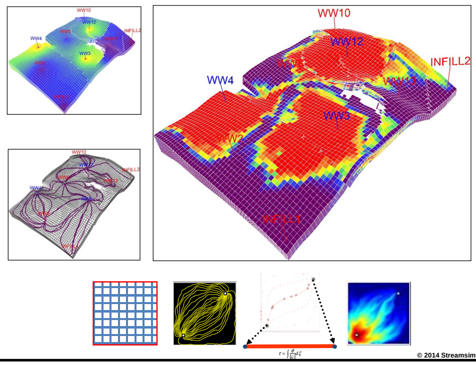


$$\frac{\partial S_w}{\partial t} + \frac{\partial f_w}{\partial \tau} = 0$$

along *each* SL

$$N_p = E_D \times E_V \times N$$

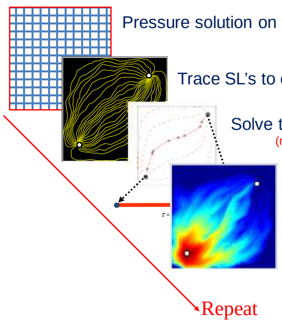
Map from SL's to Grid



Steps in SL Simulation

For each time step do:

CPU time



Pressure solution on the Eulerian grid — t^{psolve}

Trace SL's to create "dynamic" grid — $t^{sl-grid}$

Solve transport along SL-grid (not used in surveillance) — $\sum_{streamlines}^{all} t^{sl-solver}$

Map from SL's to grid (not used in surveillance)

Correct for gravity & other non-linearities (not used in surveillance) — $\sum_{gravitylines}^{all} t^{gl-solver}$

Repeat

Applicability of SL's

- Areas of applicability of SL' simulation:
  - Flow visualization
  - Surveillance
  - Reservoir/flood management
  - Ranking & uncertainty in reservoir performance
  - Upscaling
  - Dual-porosity systems
  - Miscible flooding/compositional flooding
  - History Matching
  - (Bio) Polymer Flooding and other advanced EOR techniques

Streamlines in Reservoir Surveillance

Streamlines in Reservoir Surveillance

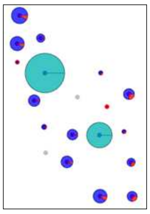
- Flanders & Bates 1987, SPE16482
- Grinestaff 1999, SPE54616
- Grinestaff & Caffery 2000, SPE63157
- Batycky et al. 2008, SPE95402-PA

SL-Based Surveillance Model

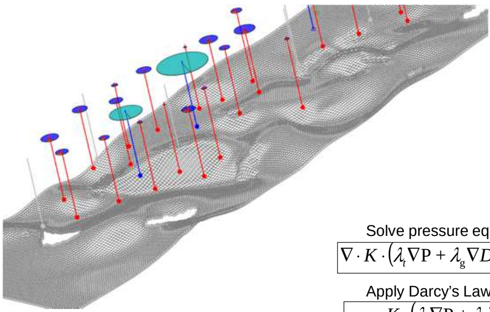
- A SL-based surveillance model is a *data-driven* flow model that requires:
  - well locations & historical rates (data)
  - a grid (2D or 3D)
  - major geologic features

Bubble map
of well rates

- oil prod
- wat prod
- wat inj



Well Rates -> Velocity Field



Solve pressure eqn.

$$\boxed{\nabla \cdot K \cdot \left(\lambda_t \nabla P + \lambda_g \nabla D\right) = q}$$

Apply Darcy's Law

$$\boxed{v = -K \cdot \left(\lambda_t \nabla P + \lambda_g \nabla D\right)}$$

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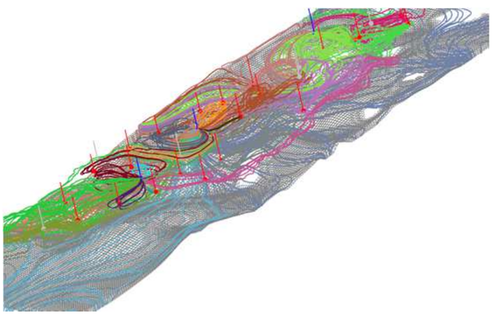
Velocity Field -> Streamlines



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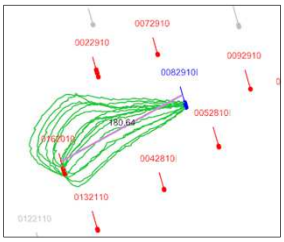
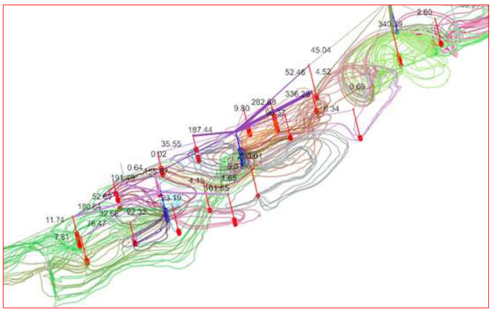
Well-Pair Flux

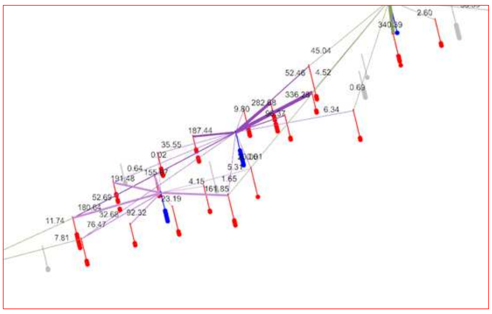
$$Q^{I-P} = \sum q_{sl}^{I-P} = 180.64\ \frac{rb}{d}$$



Well-Pair Fluxes

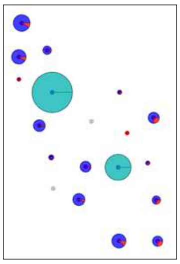


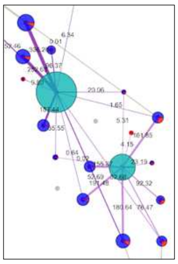
Flux Pattern Map (FPmap)



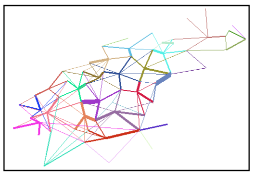
FPMap from Production Data

Bubble map
of well rates
oil prod
wat prod
wat inj



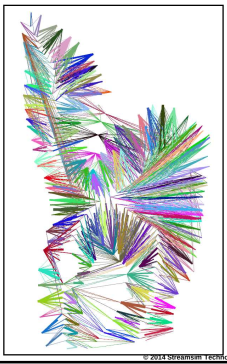


FPmaps Can Be Complicated



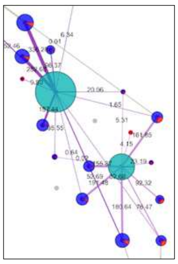
The subsurface network of pipes.

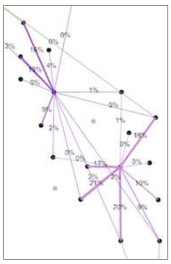
Impossible to deduce this type of sub-surface connectivity through heuristic methods.



Well Allocation Factor (WAF)

- Injector centered $WAF^{I\text{-}P} = \frac{well\ pair\ flux}{injector\ rate} = \frac{Q^{I-P}}{Q^{I}}$

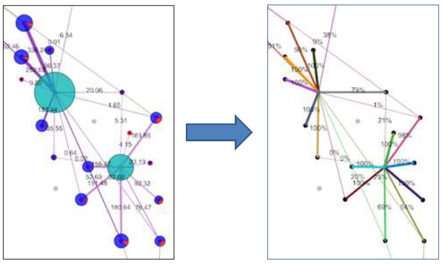




Color based on parent well
Thickness based on WAF

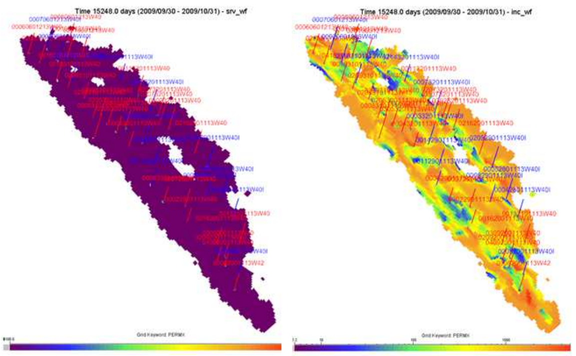
Well Allocation Factor (WAF)

- Producer centered WAF[P-I] $= \frac{well\ pair\ flux}{producer\ rate} = \frac{Q^{P-I}}{Q^P}$



Color based on parent well
Thickness based on WAF

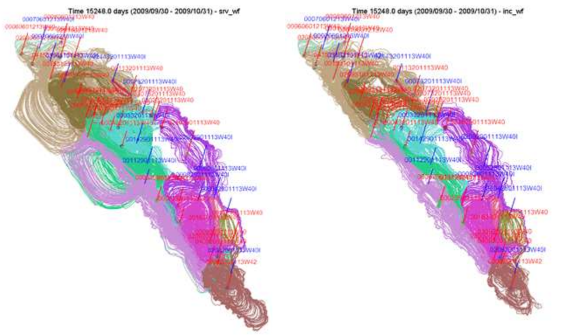
Well-Pairs and Heterogeneity



Surveillance model

Detailed Flow Model

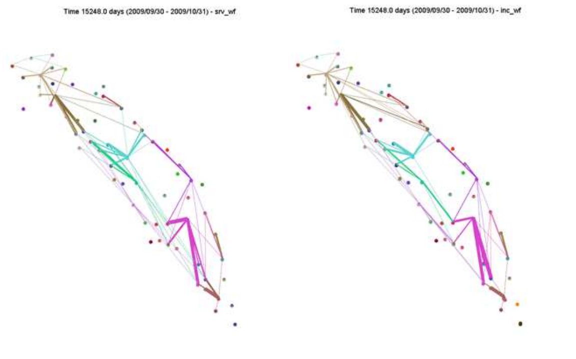
Well-Pairs and Heterogeneity



Surveillance model

Detailed Flow Model

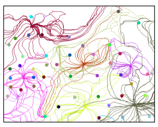
Well-Pairs and Heterogeneity



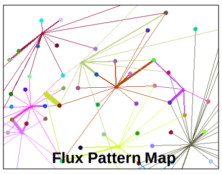
Surveillance model **Detailed Flow Model**

Streamline-Based Surveillance

- Not interested in the details of individual SL paths.
- The total flow rate of the streamline bundle between each well-pair is sensitive to:
  - Well rates
  - Well locations
  - Reservoir connectivity (geology)



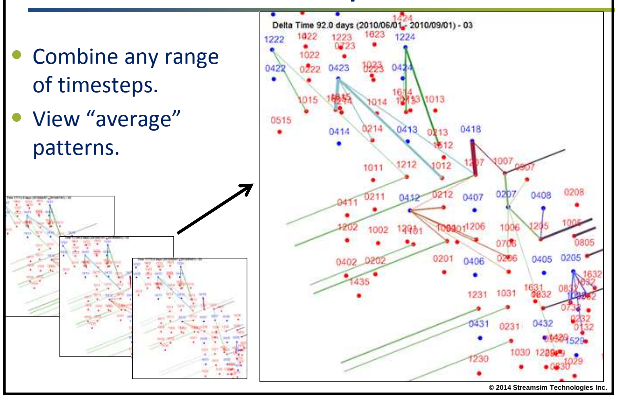
Streamlines



Flux Pattern Map

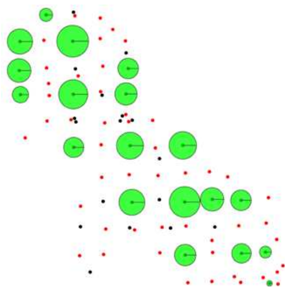
Cumulative FPmap

- Combine any range of timesteps.
- View "average" patterns.

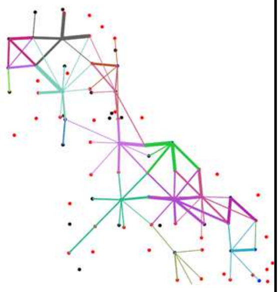


Bubbles vs FPmap

Cum Water Injection



Cum Water Injection

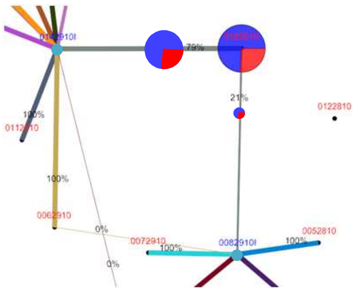


FPmap is a "flow-based" bubble map.

Back-Allocate Historical Production Rates

- Same back-allocation method as with geometric-based WAF's.

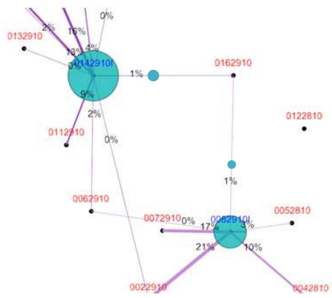
Well-Pair Production Rates = WAF^{P-1} x



Forward-Allocate Historical Injection Rates

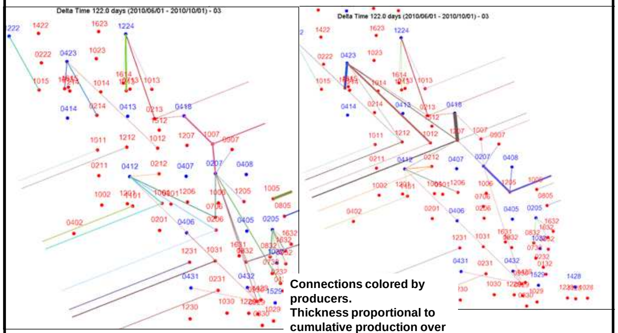
- Same allocation method as with geometric-based WAF's.

Well-Pair Injection Rates = WAF^{I-P} x



Average Patterns: Cycling vs Efficient

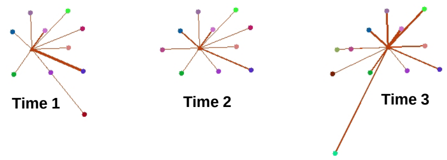
Connections Cum oil prod **Connections Cum wat prod**



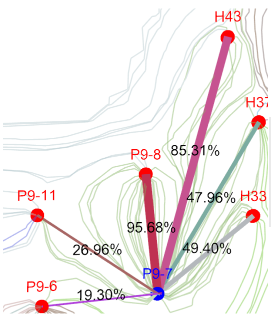
Connections colored by producers. Thickness proportional to cumulative production over time range (rm3).

Injector Centered Patterns

- Flow is not limited to fixed patterns and there can be significant off-pattern flow.
  - Why classify this flow as influx/efflux and associate with a different pattern?
- To quantify the true effectiveness of an injector, associate <u>all</u> of the production it is responsible for.
- Surveillance for improved sweep management vs VRR management.



WAF's –> Injector Efficiency



Per-injector

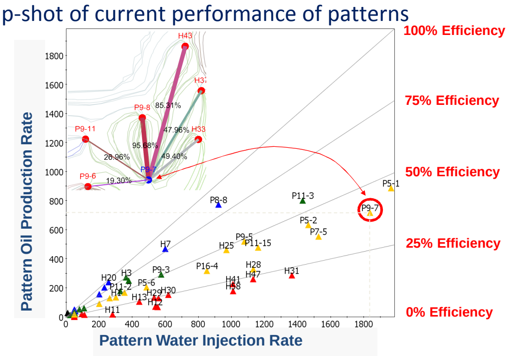
Off-set oil production due to injector P9-7:

$$Q_o^{P9-7} = 0.19\times Q_o^{P9-6} + 0.27\times Q_o^{P9-11} + 0.96\times Q_o^{P9-8} + 0.85\times Q_o^{H43} + 0.48\times Q_o^{H37} + 0.49\times Q_o^{H33}$$

$$\boxed{I_{eff} = \frac{\text{off-set oil production [rb/day]}}{\text{water injection [rb/day]}}}$$

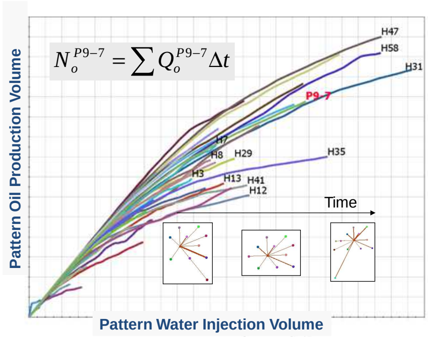
The Pattern Efficiency Plot

- Snap-shot of current performance of patterns



The Conformance Plot

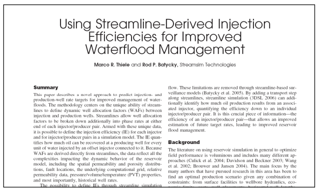
- Overall performance of patterns



SL-Based Surveillance

- SL-based surveillance model
  - Use SL geometries to calculate flow-based WAF's
  - Back-allocate production data to injector-centered patterns
  - No predictive capabilities, not "flow simulation"
  - Computationally light
  - Data-driven model
- Powerful per pattern metrics
  - FPmap (flow-based allocation factors)
  - Current Pattern efficiencies
  - Conformance plot

Flood Management via Well Rate Targets



Using Streamline-Derived Injection Efficiencies for Improved Waterflood Management

Marco R. Thiele and Rod P. Batycky, Streamsim Technologies

Summary

This paper describes a novel approach to predict injection- and production-well rate targets for improved management of waterfloods. The methodology centers on the unique ability of streamlines to define dynamic well allocation factors (WAFs) between injection and production wells. Streamlines allow well allocation factors to be broken down additionally into phase rates at either end of each injector/producer pair. Armed with these unique data, it is possible to define the injection efficiency (IE) for each injector and for injector/producer pairs in a simulation model. The IE quantifies how much oil can be recovered at a producing well for every unit of water injected by an offset injector connected to it. Because WAFs are derived directly from streamlines, the data reflect all the complexities impacting the dynamic behavior of the reservoir model, including the spatial permeability and porosity distributions, fault locations, the underlying computational grid, relative permeability data, pressure/volume/temperature (PVT) properties, and most importantly, historical well rates.

flow. These limitations are removed through streamline-based surveillance models (Batycky et al. 2005). By adding a transport step along streamlines, streamline simulation (3DSL 2006) can additionally identify how much oil production results from an associated injector, quantifying the efficiency down to an individual injector/producer pair. It is this crucial piece of information—the efficiency of an injector/producer pair—that allows an improved estimation of future target rates, leading to improved reservoir flood management.

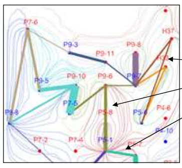
Background

The literature on using reservoir simulation in general to optimize field performance is voluminous and includes many different approaches (Culick et al. 2004; Davidson and Beckner 2003; Wang et al. 2002; Brouwer and Jansen 2004). The main focus by the many authors that have pursued research in this area has been to find an optimal production scenario given any combination of constraints: from surface facilities to wellbore hydraulics, eco-

SPEREE April 2006

Managing Brown Fields Using SL's

- Identify good/bad patterns using SL's.
- To impact sweep, increase/ decrease rates at *both* producers and injectors.
- Goal => Best use of injected volumes for displacement purposes, not re-pressurization.
- "Poor mans" waterflood optimization.



For each connection determine:

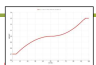
$$I_{eff} = \frac{\text{off-set oil production [rb/day]}}{\text{water injection [rb/day]}}$$

equivalent to "Oil Cut"

New Target Rates

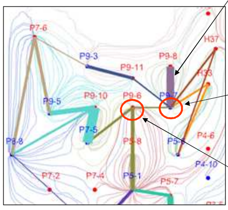
A heuristic workflow rather than formal optimization.

weighting function



$$q_{new}^{9-7/9-8} = q_{old}^{9-7/9-8} \times w(I_{eff})$$

New total rate of connection 9-7/9-8



New Injection Rate
(sum all connections)

$$q_{new}^{9-7} = \sum q_{new}^{9-7/x}$$

New Production Rate
(sum all connections)

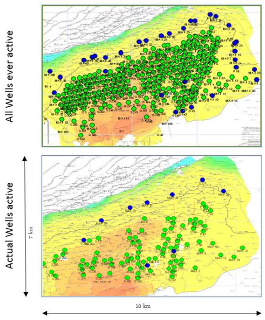
$$q_{new}^{9-6} = \sum q_{new}^{9-6/x}$$

Case Studies

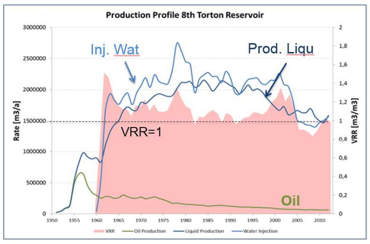
- Thulielat heavy-oil waterflood, South Oman, 2011/2012. 6 month results:
  - Changed rates for 6 injectors, 0 net injection rate change
  - +35m3/d oil
- 8th Tortonian Field, Austria, 2010/2012. 2.5 years of results:
  - +35000 STB oil (incremental not accelerated)
  - Shut in oil production

8th Tortonian

- The 8th reservoir is part of the Matzen Field, Austria
- Average depth: -1100 TVDSS, average pay is 20m
- Sandstone reservoir, 4 layers with limited cross-flow
- Other
  - Pi: 113 bars
  - μ: 19 cp
  - ϕ=27%
  - K=100-2000md
  - P=60-100bars



Historical



Currently 87 prod, 9 inj—339 producers since 1950

Production start: Mar. 1950
Injection start: Nov. 1960

90% of wells producing with sucker rod, rest gas lift

$\bar{Q}_{oil}$ =2 m3/day (16 bbl/day)
$\bar{Q}_{total}$ =50-100 m3/day (350-700 bbl/day)

Long production tails are excellent candidates for engineered rate changes; opportunity to perturb "entrenched" flood patterns.

Reservoir Management

Goals

Increase oil rate via improved rate management/flood performance

Find an efficient and easy approach to address more wells simultaneously

Challenges

No workovers of wells (no new perforations)

No change of existing pump installations

Stay within surface facility capacities

All planning's belong to the field office

Constraints

Production/ Injection rates (limited capacities in the water treatment plant and gathering station)

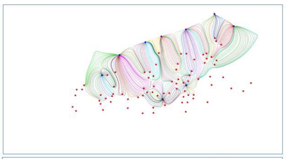
Keep Installed pump sizes and pumping jacks

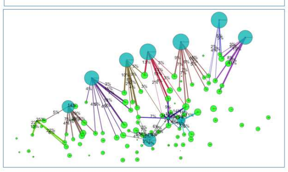
No 3D geological model available

No Simulation available

Needs a new way of thinking and approach

SL-Based WAFs





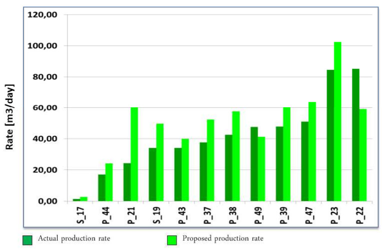
Streamline model

Simple streamline model using 2D grid with homogenous and isotropic properties

Extract WAF`s

WAF and I/P connections extracted from SL-based prod/inj data at each time step

How to get new rates?



FP Map

Gives the connections and there value

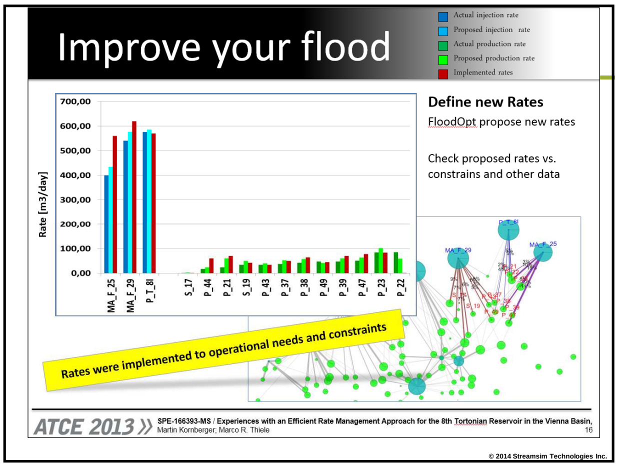
Algorithm

Is used to calculate new improved target rates based on an weighting function*

New Rates

Rates are proposed for each Well – Injector and Producer

* Thiele & Batycky SPEREE April 2006


Improve your flood
Actual injection rate
Proposed injection rate
Actual production rate
Proposed production rate
Implemented rates
Rate [m3/day]
700,00
600,00
500,00
400,00
300,00
200,00
100,00
0,00
MA_F_25
MA_F_29
P_T_8I
S_17
P_44
P_21
S_19
P_43
P_37
P_38
P_49
P_39
P_47
P_23
P_22
Define new Rates
FloodOpt propose new rates
Check proposed rates vs. constrains and other data
Rates were implemented to operational needs and constraints
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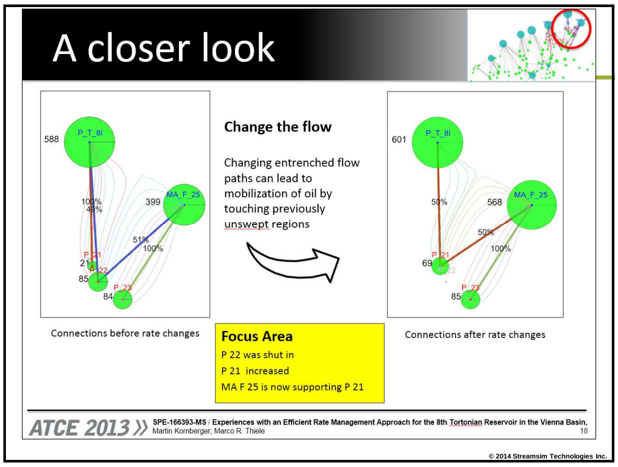
A closer look
P_T_8I
588
399
MA_F_25
100%
49%
51%
100%
P_21
P_22
P_23
21
85
84
Connections before rate changes
Change the flow
Changing entrenched flow paths can lead to mobilization of oil by touching previously unswept regions
601
568
50%
50%
100%
69
85
Connections after rate changes
Focus Area
P 22 was shut in
P 21 increased
MA F 25 is now supporting P 21
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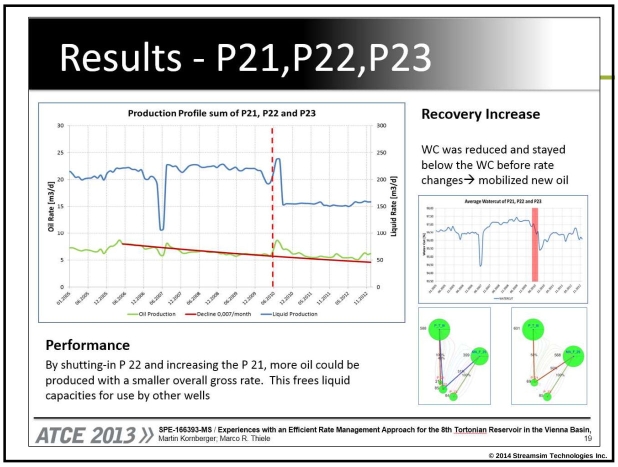
Results - P21,P22,P23
Production Profile sum of P21, P22 and P23
Oil Rate [m3/d]
Liquid Rate [m3/d]
Oil Production
Decline 0,007/month
Liquid Production
Recovery Increase
WC was reduced and stayed below the WC before rate changes→ mobilized new oil
Performance
By shutting-in P 22 and increasing the P 21, more oil could be produced with a smaller overall gross rate. This frees liquid capacities for use by other wells
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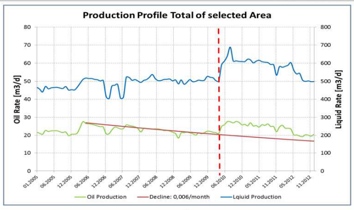
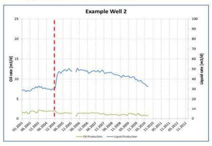
Results - All Wells

Do the right thing!!!





Performance

Additional ~35 k bbl of oil could be produced to date

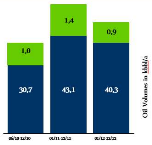
Actual Oil Production Increase for 2,5 Year >30%

Investments

No additional Work Over - No additional perforation

All actions within constrains

Less than 10K € were spent



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Rate Management Workflow

1. Use production data to determine flow-based allocation factors and efficiencies.
2. Use SL-metrics to help set fluid target rates
3. Implement targets and wait for the reservoir to respond.
4. Update surveillance model with latest production data.
5. Repeat…

Rate Management Conclusions

- Flood management can be as low-cost and simple as rebalancing well-rates.
- To be most effective, rate changes at *both* producers and injectors are required.
- Knowing well-pairs allows a heuristic and quantifiable workflow to reduce fluid cycling and increase oil production rates. Not formal optimization.
- Case studies using flow-based allocation factors show incremental oil recovery.

Summary/Conclusions

- SL's offer two new RE surveillance metrics:
  - Dynamic connectivity maps of inj/prod support.
  - Injector efficiencies (per-pair, per-pattern, instantaneous and over time).
- Patterns are injector centered, dynamic, robust, and quantifiable.
- SL-Based surveillance + rate-rebalancing guided by well-pairs, gives a methodical workflow based on field response, resulting in incremental oil production.
- SL's may not be applicable to all fields, but every mature pattern waterflood should have a SL-Based surveillance model.
- These metrics and workflow naturally extend to miscible, CO_2, and polymer floods.