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Streamline Reservoir Flow Models to Improve Mature Floods by Low-Cost Actions

Rod P Batycky
Streamsim Technologies, Inc.

Society of Petroleum Engineers
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Mature Fields Today

- *"Mature fields are in declining production reaching the end of their lives."* – petrowiki.spe.org

- *"70% of world oil production (59 MMb/d) is from mature fields"* – Offshore Magazine Oct 2019

- Oil Price collapse in April 2020

- *"I have found operators focusing on making all-out efforts to improve their ongoing waterflood operations to extend the life of existing wells, which is preferred over drilling new infill wells"* – R.V. Marathe - Jan 2021 SPE-JPT

- Not all decisions require flow simulation models. Use 'numerically lighter' surveillance models to improve ongoing waterflood operations of existing wells

Outline

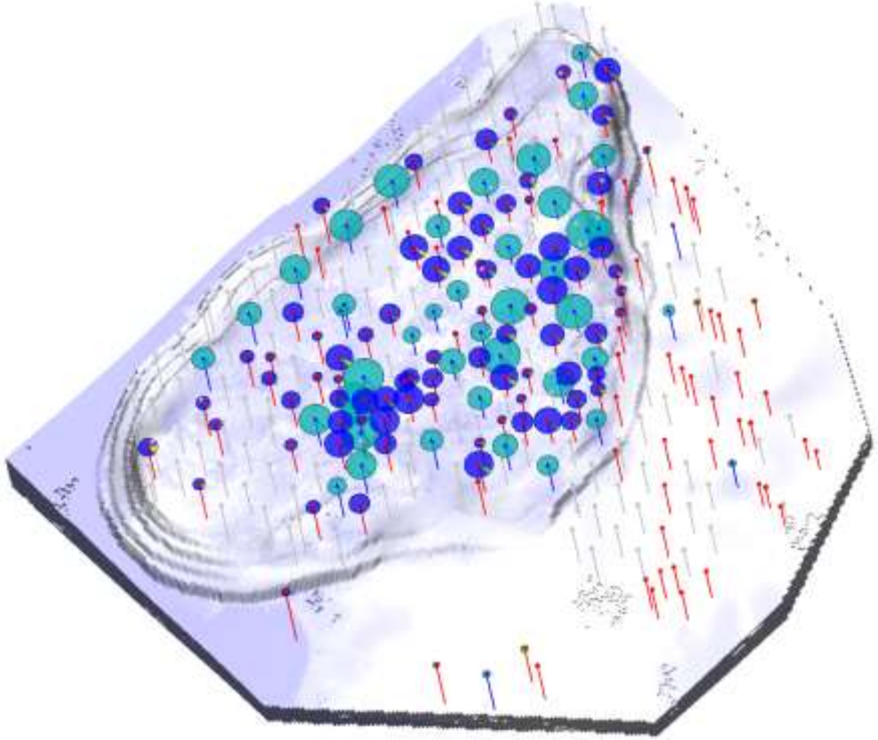
- Reservoir Surveillance Using Streamlines
  - Injector patterns
  - ROIP
  - Rapid forecasting
- Mature Field Management
  - Pattern realignment
  - Field Example
- Summary

Mature Flood Management Forecasting

- Not all decisions require flow simulation models. Use ‘numerically lighter’ surveillance models to improve ongoing waterflood operations of existing wells

time
resources
precision

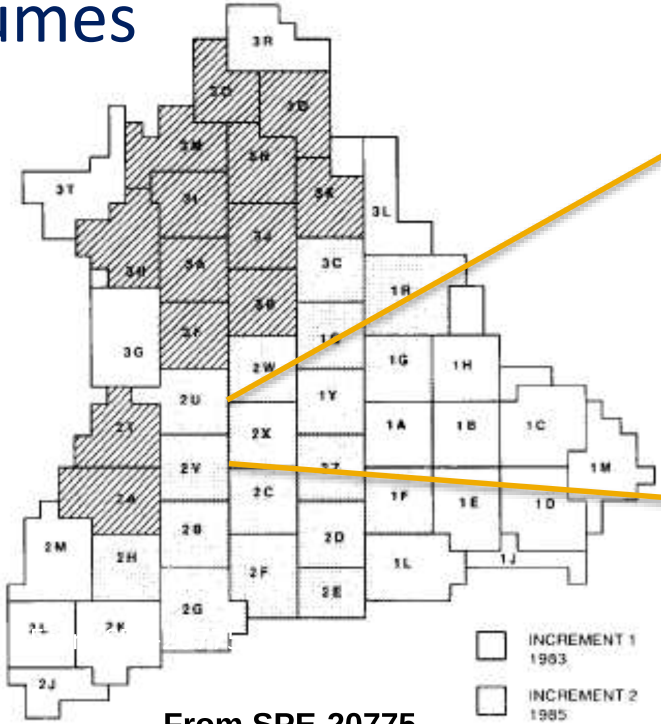
- Reservoir forecasting tools
  - Decline analysis & type curves
  - Material Balance
  - Capacitance Resistance Models (CRM)
  - Machine Learning Models
  - Streamline Surveillance
  - Simulation (streamlines or finite-difference)



Reservoir Pattern Surveillance

Traditional reservoir pattern surveillance is the association of produced and injected volumes

- Define well-pairs
- Define fixed patterns
- Pattern recoveries
- Well rate targets to balance patterns



From SPE-20775

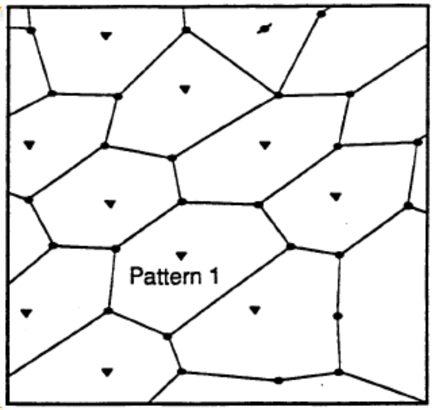


Fig. 1- Pattern Example

From SPE-35202

How are well-pairs identified?

- Defined by geometry -> 80's technology
- Defined based on flow rates -> modern streamline surveillance

Surveillance vs. Simulation

Surveillance Used for short-term management and optimization.

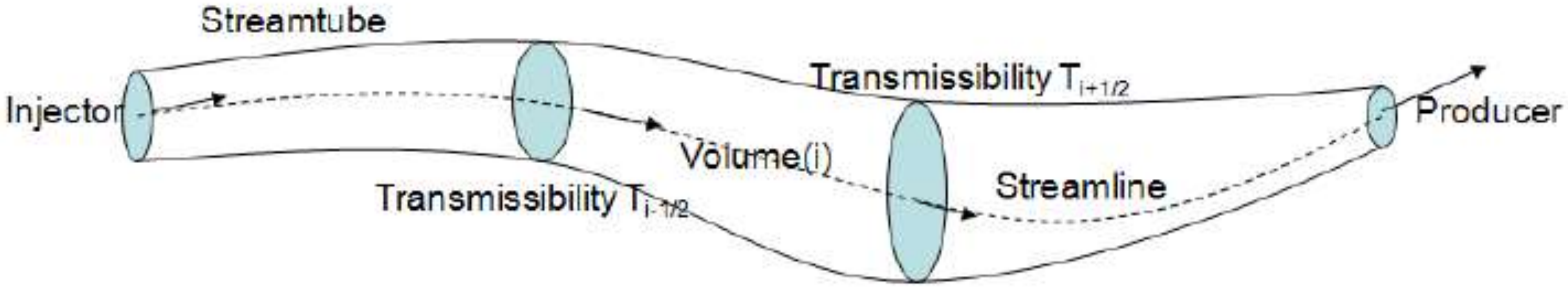
- Flow-based 3D numerical model with pressure solution
- Historical rates are used directly (Data-Driven)
- Well-pairs & well-patterns calculated numerically
- Saturations and pressures from dynamic material balance
- Rapid forecasting

Simulation Used for mid/long term forecasting and what-if scenarios of capital intensive projects.

- Flow-based 3D numerical model with coupled pressure and transport equations
- Requires expert knowledge to build and use
- Requires time to history match

What is a streamline?

- A streamline (or streamtube) is a path in 3D that follows the velocity field.

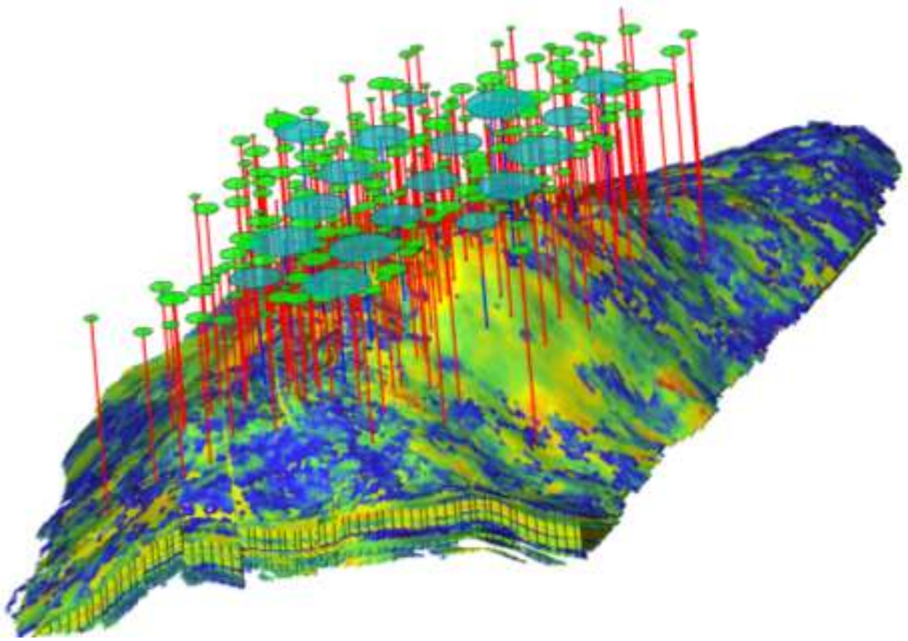


- Streamlines start at sources and end at sinks.

Streamlines in a Mature Field

3D grid
- basic geology
- major flow units

Wells
- Locations
- prod/inj rates

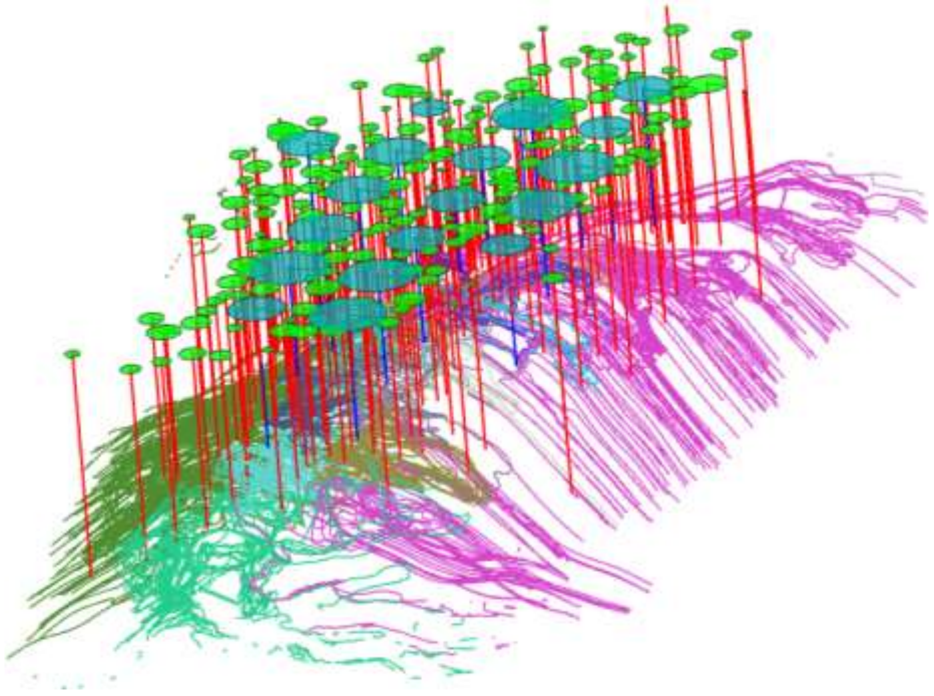


PVT
+
Saturations
Pressures

Streamline Simulator

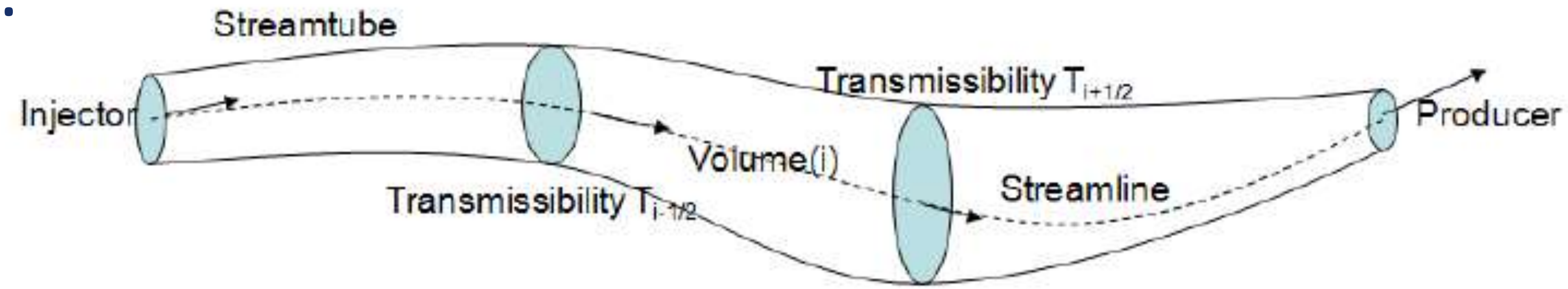
$$\nabla \cdot K \cdot \left(\lambda_t \nabla P + \lambda_g \nabla D\right) = q$$

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



Properties of Streamlines

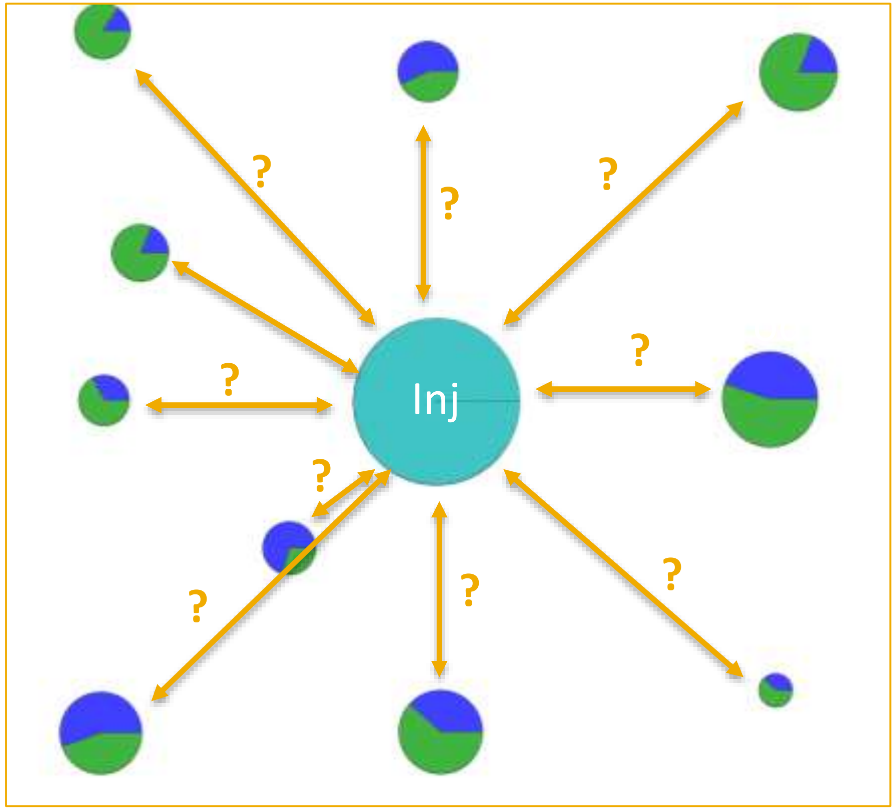
- A streamline (or streamtube) is a path in 3D that follows the velocity field.



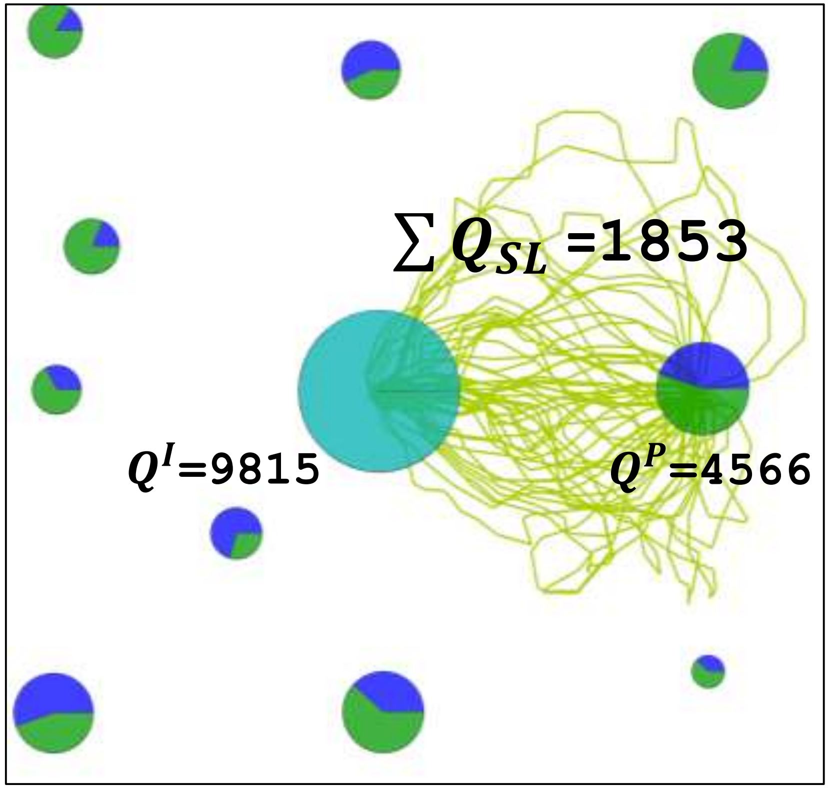
- Streamlines start at sources and end at sinks.
- For each streamline we know:
  - The inj/prod relationships
  - The total flow rate (flux)
  - The pore volume

Injector Centered Pattern

- Extract I-P connections from measured inj/prod volumes:
  - What % of injected volume supports a producer?
  - What % of produced volume is supported by an injector?

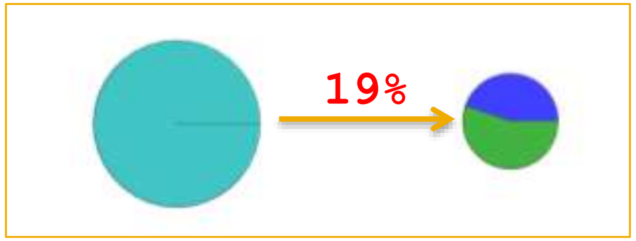


Well Rate Allocation (WAF) From Well-Pair Flux

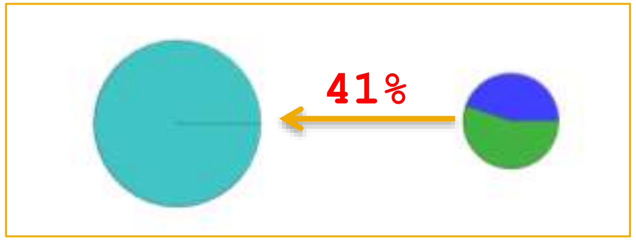


Solve for streamlines and consider bundle connecting **I-P** pair.

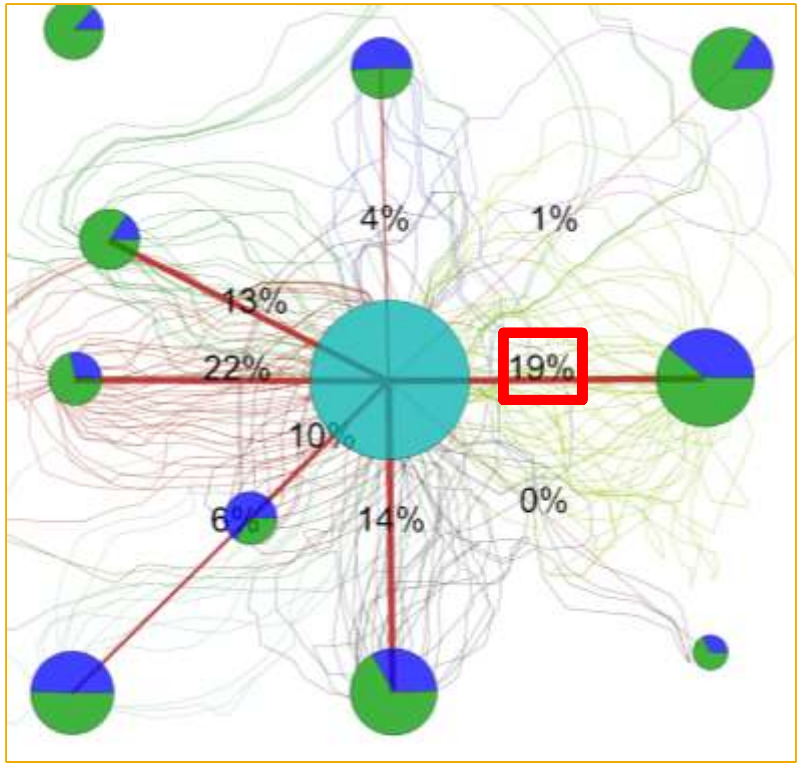
1853/9815 = 19% → Percentage of injected fluid from **I** supporting production at **P**



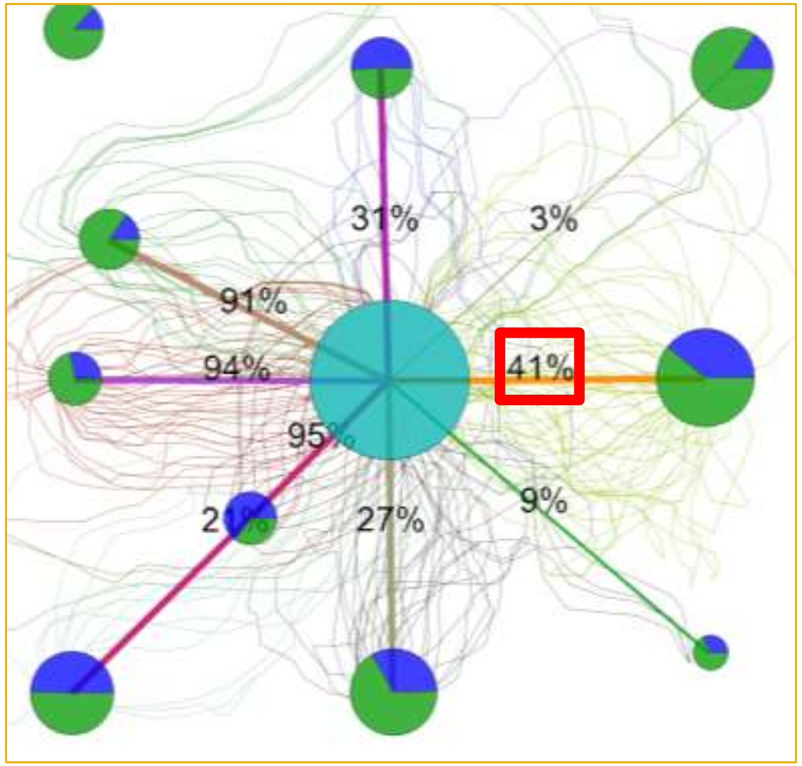
1853/4566 = 41% → Percentage of produced fluid at **P** due to injection at **I**



Well Allocation Factors



Injector-centered WAFs

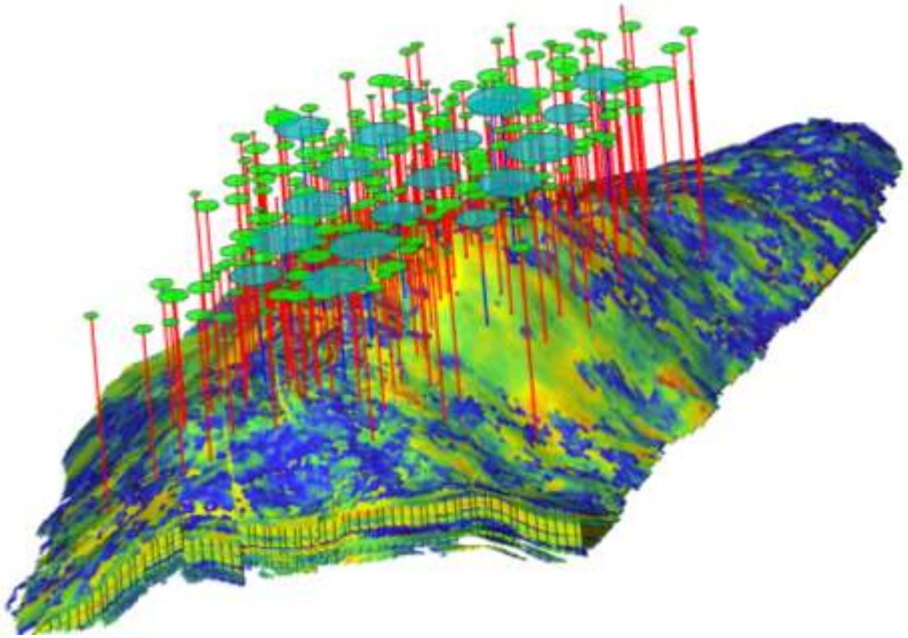


Producer-centered WAFs

Injector-Patterns in a Mature Field

3D grid
- basic geology
- major flow units

Wells
- Locations
- prod/inj rates



PVT
+
Saturations
Pressures

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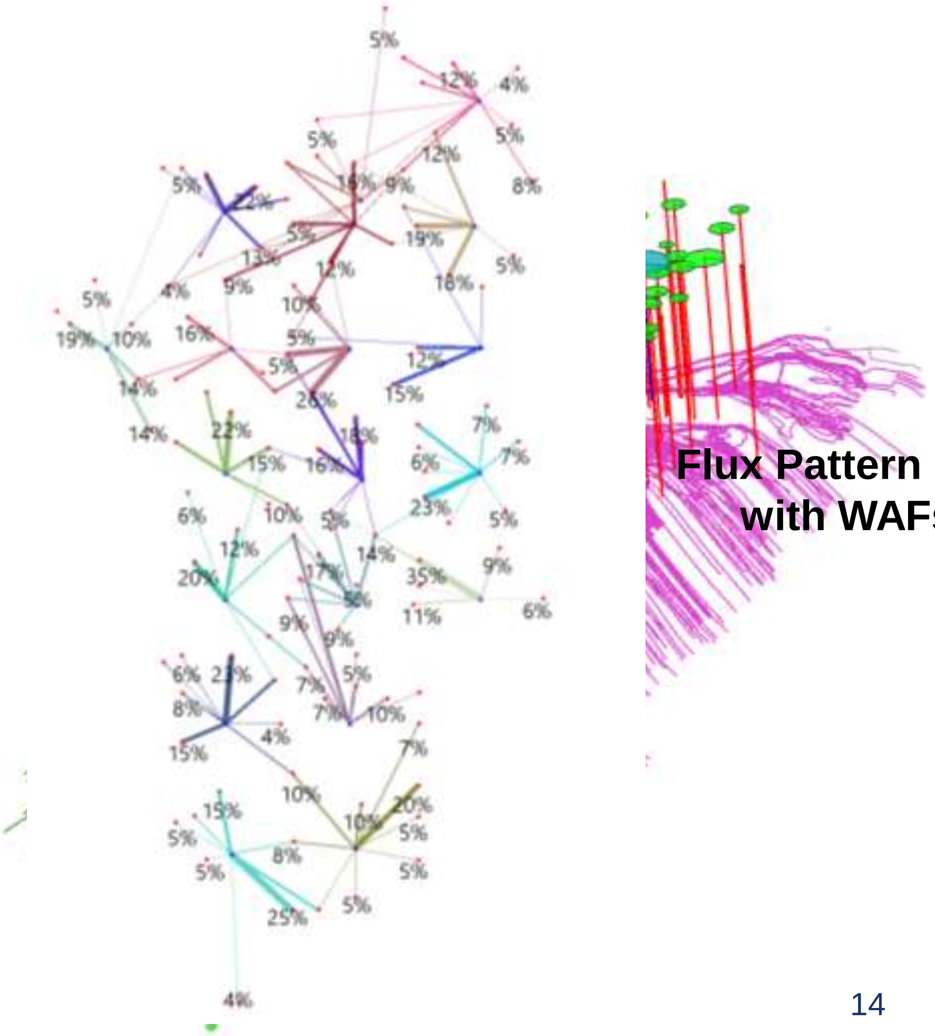

Flux Pattern Map with WAFs

FPmap Animation

As rates change through time, so does the FPmap and consequently the patterns.

Injector Voidage Rate

Producer Voidage Rate

Injector Pattern Efficiency

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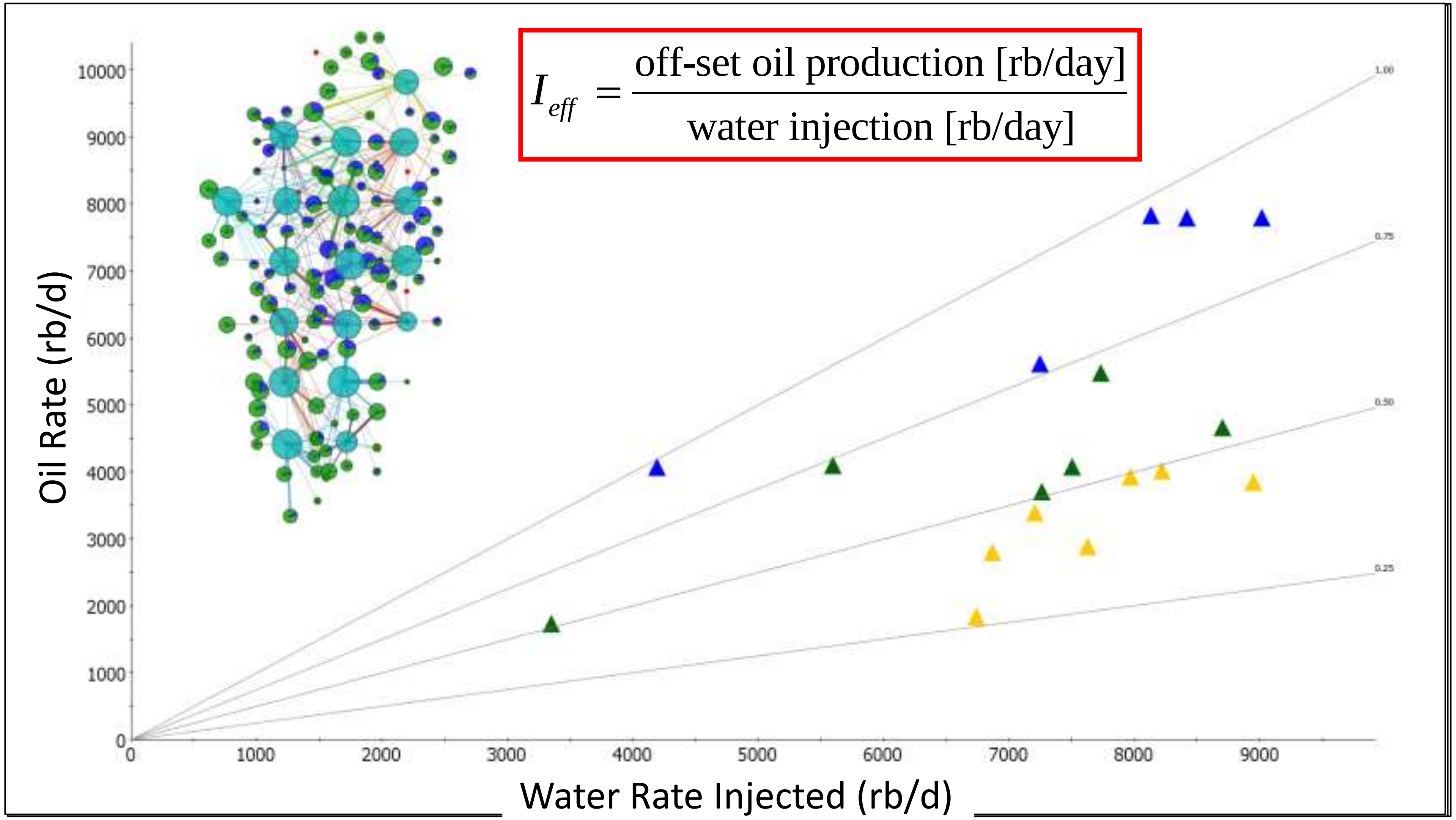
Once the pattern (injector or producer centered) is defined, associate oil production with injection.

Efficiency of an injector pattern:

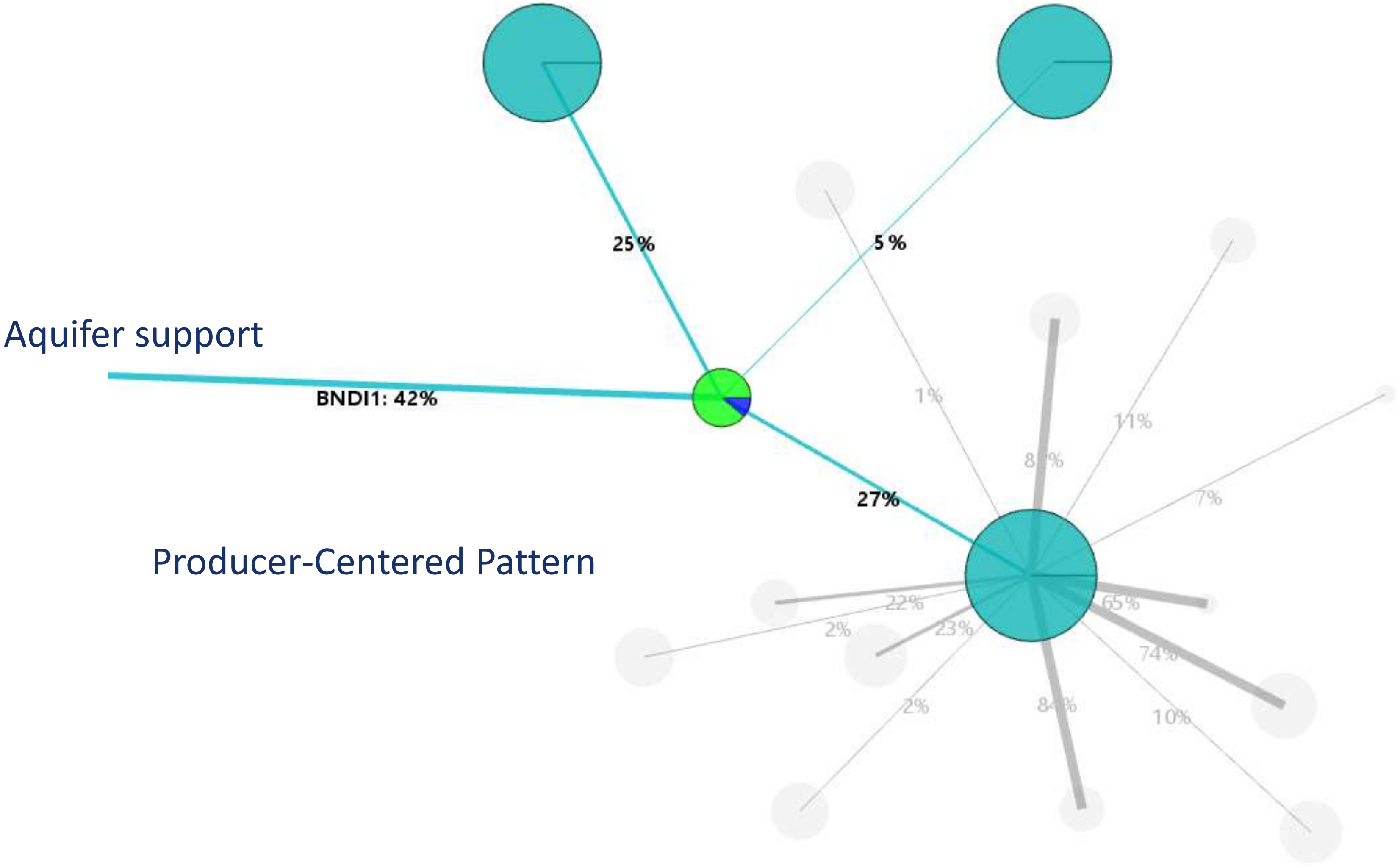
$$I_{eff} = \frac{\text{offset oil volume produced from pattern}}{\text{volume injected into pattern}}$$

volume injected can be water, CO_2, polymer, solvent

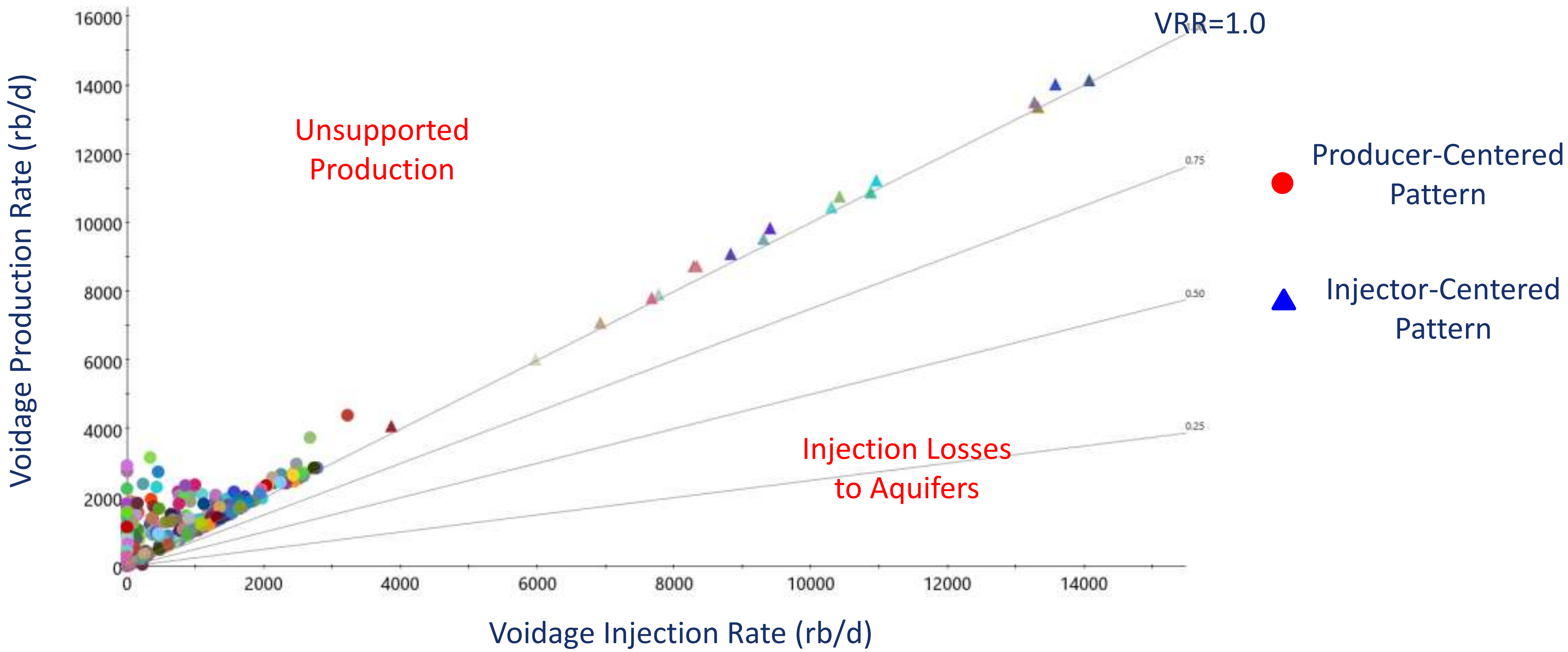
Injector Efficiency for the Field



Producer-Centered Pattern

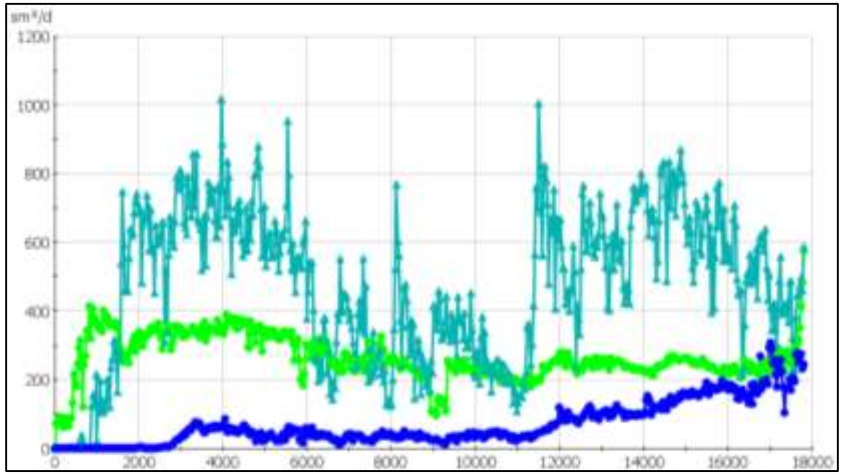


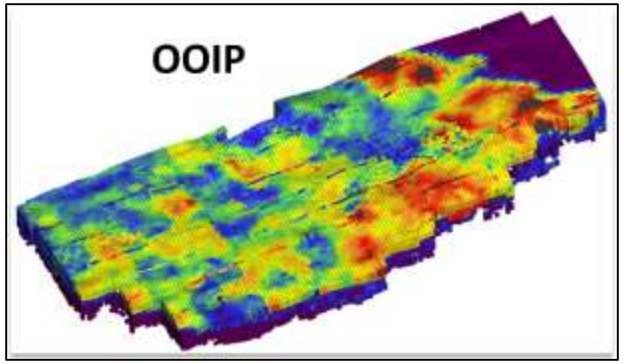
Pattern VRR for Field

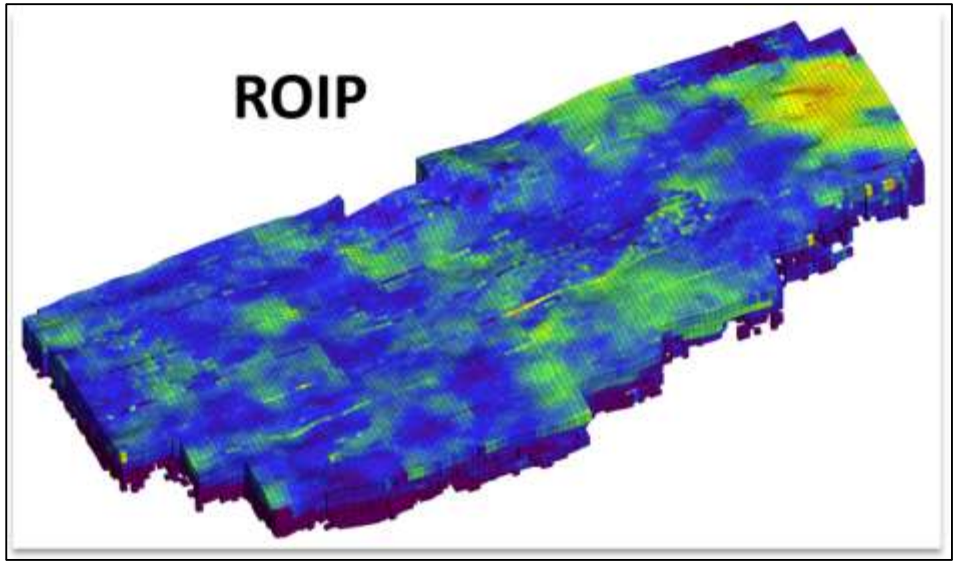


From Dynamic Patterns to Remaining Oil In Place (ROIP)

Given pattern bundles, allocation factors, Original Oil in Place, and historical prd/inj rates, apply dynamic well-pair material balance (SPE185713-PA).







Remaining Oil In Place

Material Balance Applied to a Well-Pair

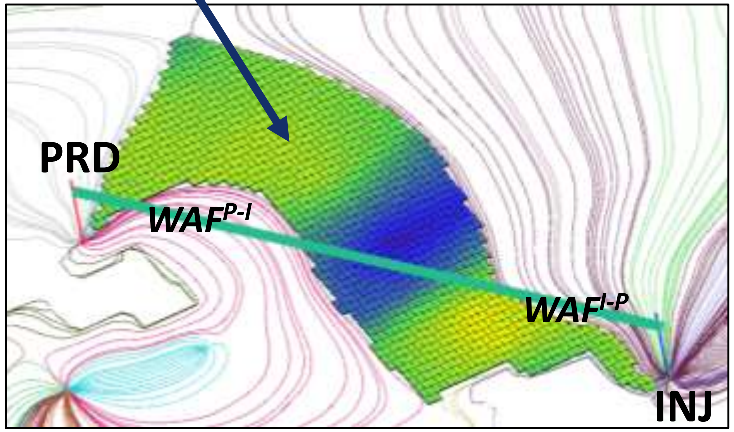
Volume of water injected

$$V^{I}_{w,\Delta t_i} = Q^{I}_{w} \times WAF^{I-P} \times \Delta t_i$$

Volume of water produced

$$V^{P}_{w,\Delta t_i} = Q^{P}_{w} \times WAF^{P-I} \times \Delta t_i$$

$V^{in-place}_{w,t_i}$ Volume of water in-place

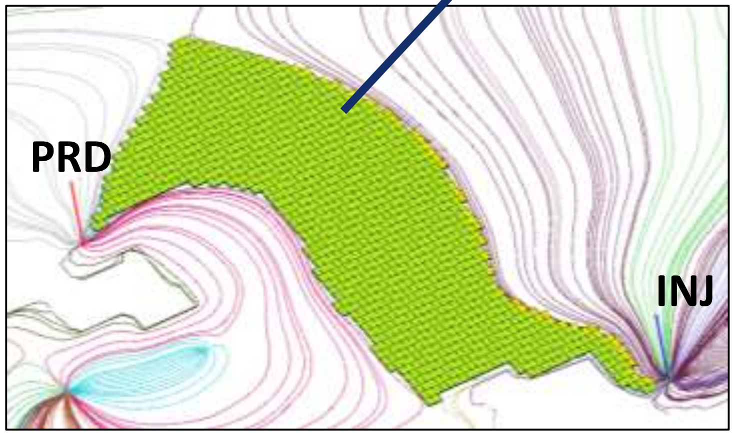


Material Balance

$$V^{in-place}_{w,t_i} + V^{I}_{w,\Delta t_i} - V^{P}_{w,\Delta t_i} = V_{w,t_i+\Delta t_i}$$

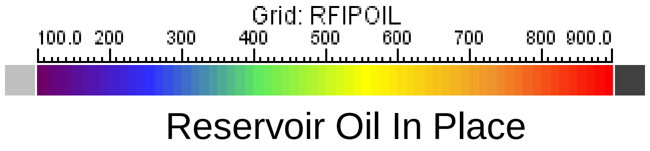
Updated average saturation

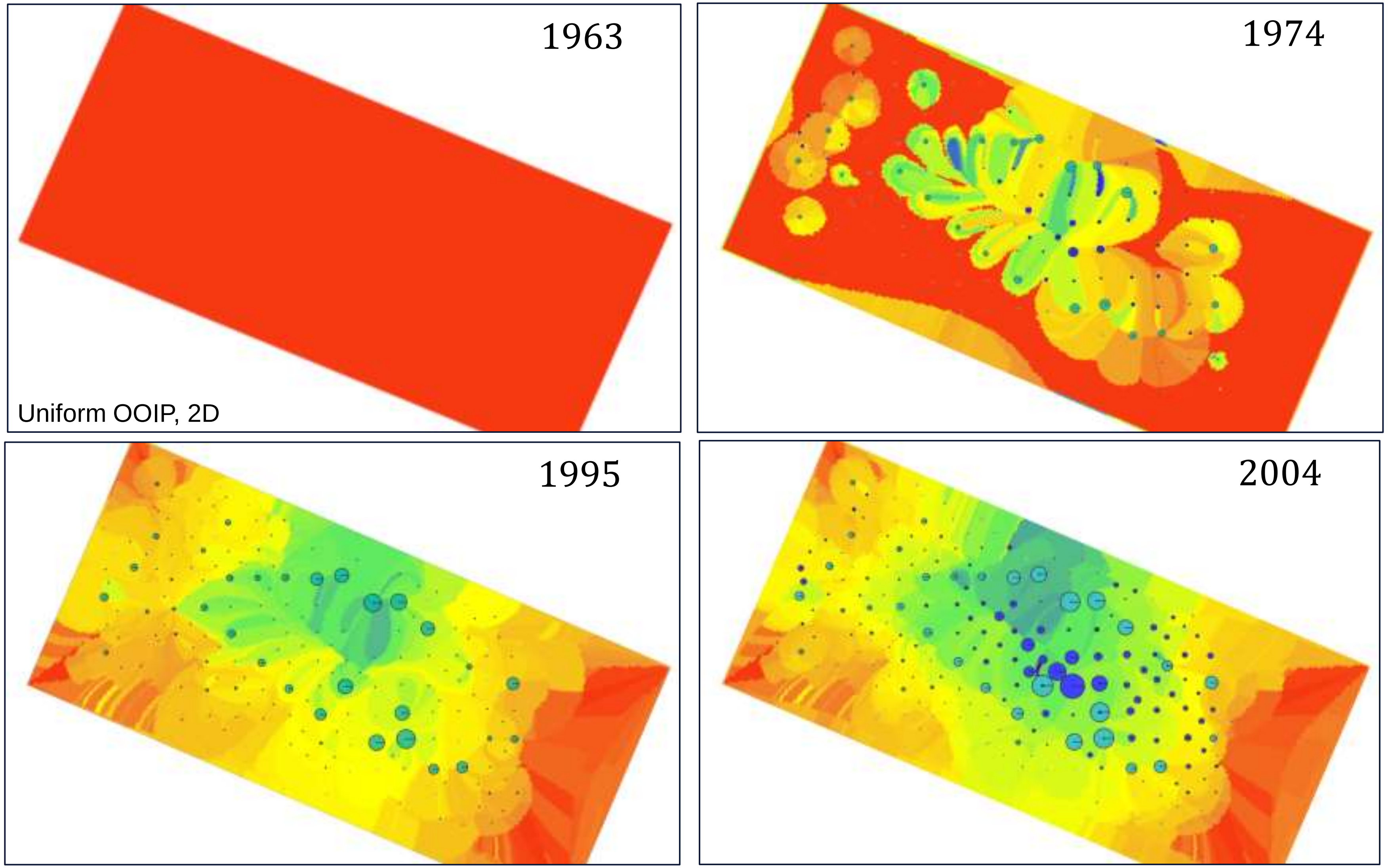
$$V_{w,t_i+\Delta t_i} \big/ V_{cv} = S_{j,t_i+\Delta t_i}$$



SPE185713-PA

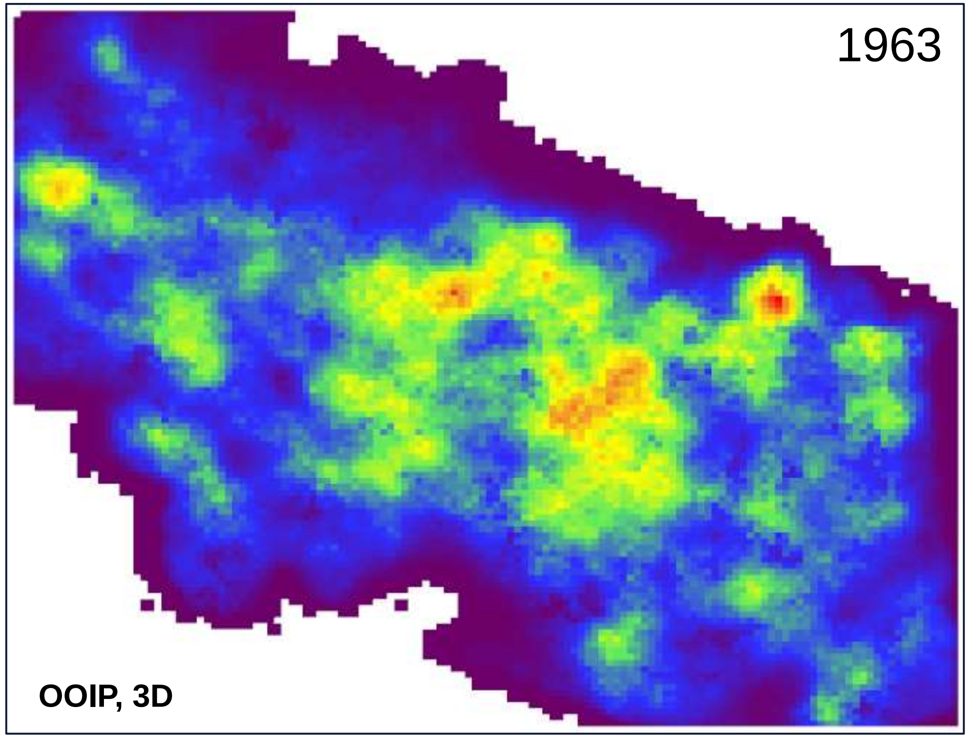
Updating Oil-In-Place Through Time



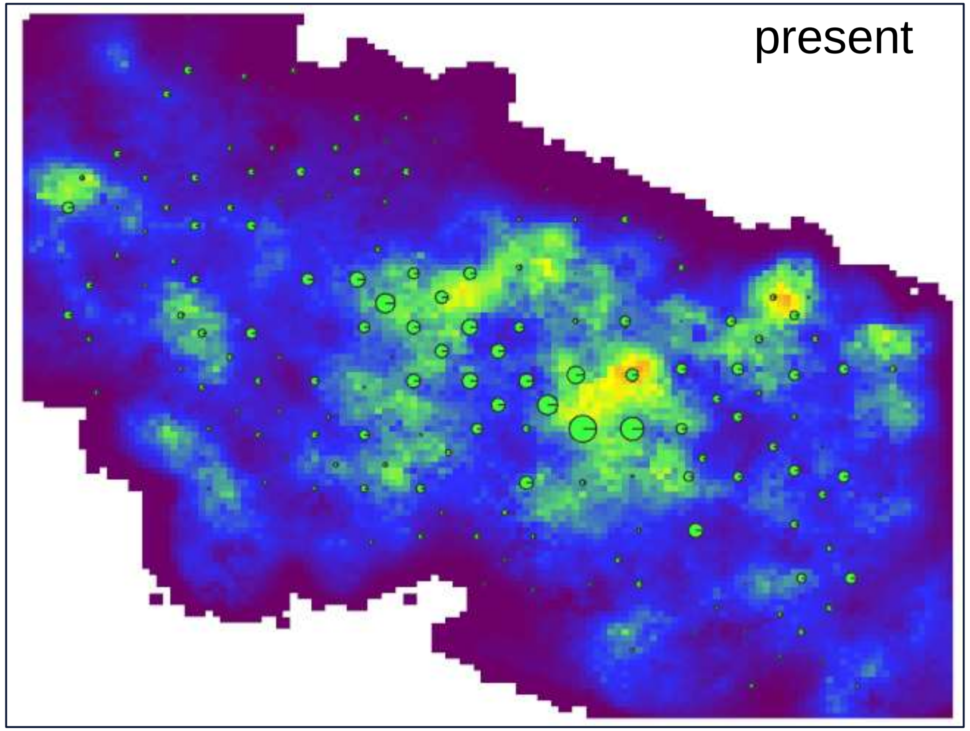


Calculate ROIP by Dynamic Well-Pair Material Balance

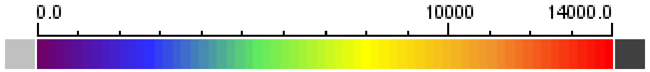
OOIP



ROIP



Reservoir Oil In Place



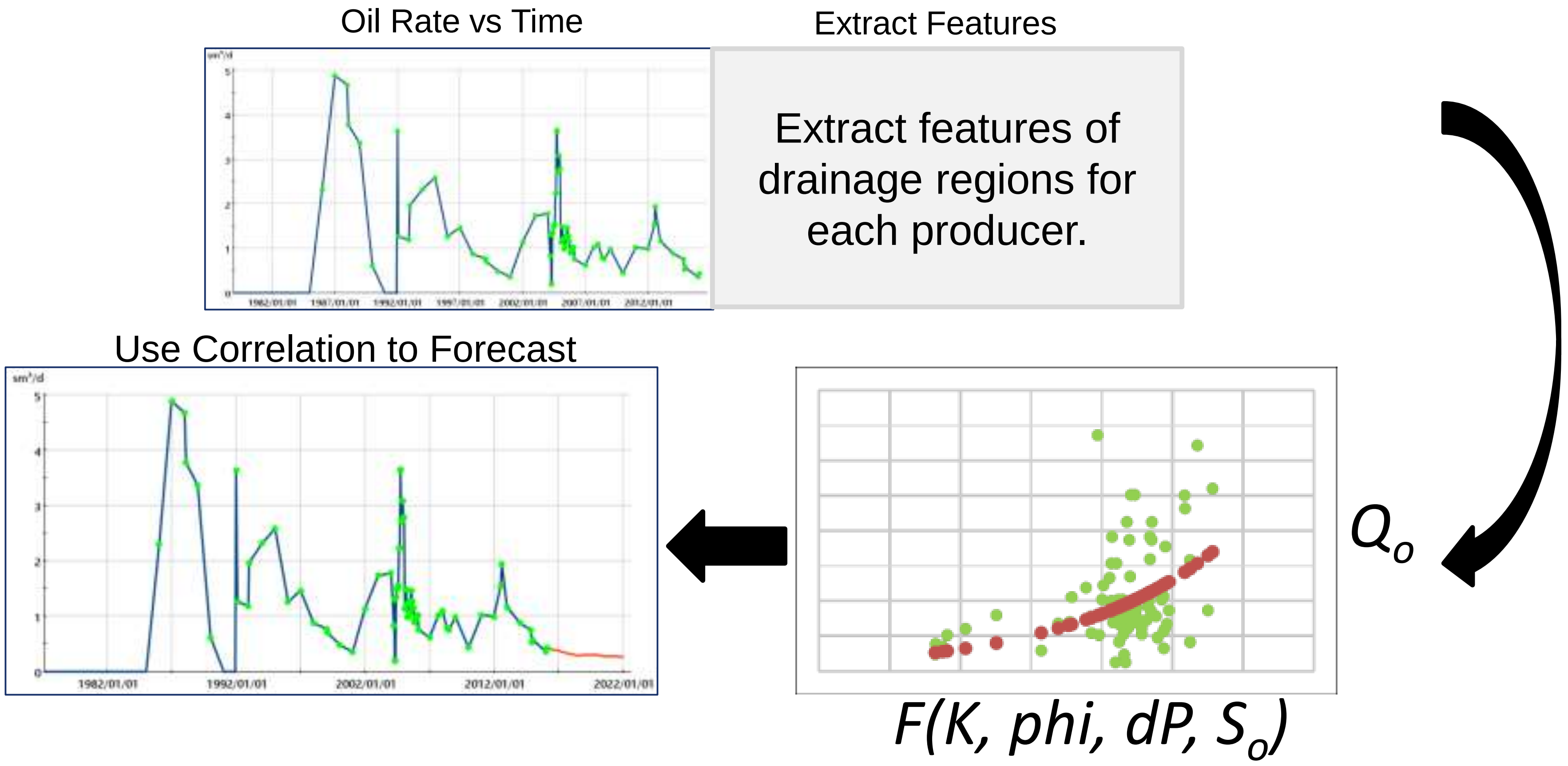
Forecasting without Flow Simulation

- Forecasting with reservoir simulation is possible because of the solution to the transport equations

- Flow-based surveillance model is Data-Driven
  - History is used directly -> No history matching
  - Well level-forecast is based on correlating history to grid properties
  - Rapid forecasting

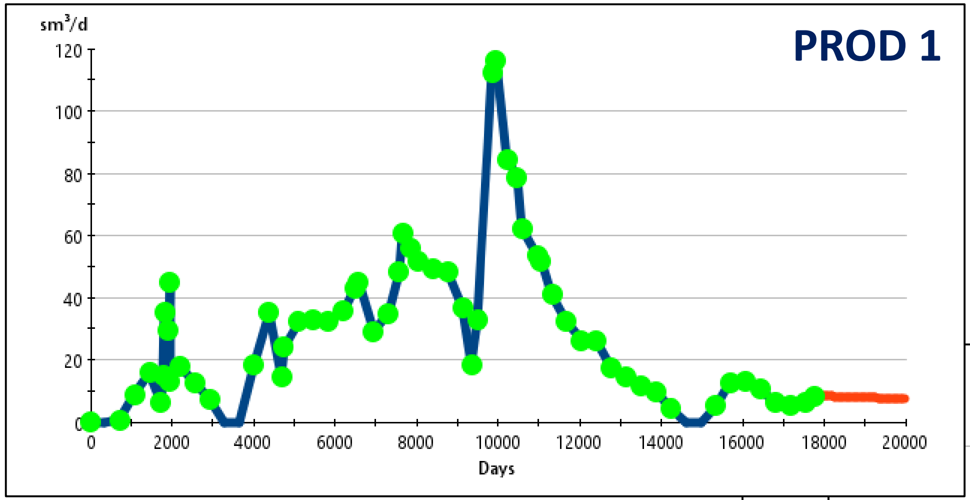
Forecasting a Surveillance Model

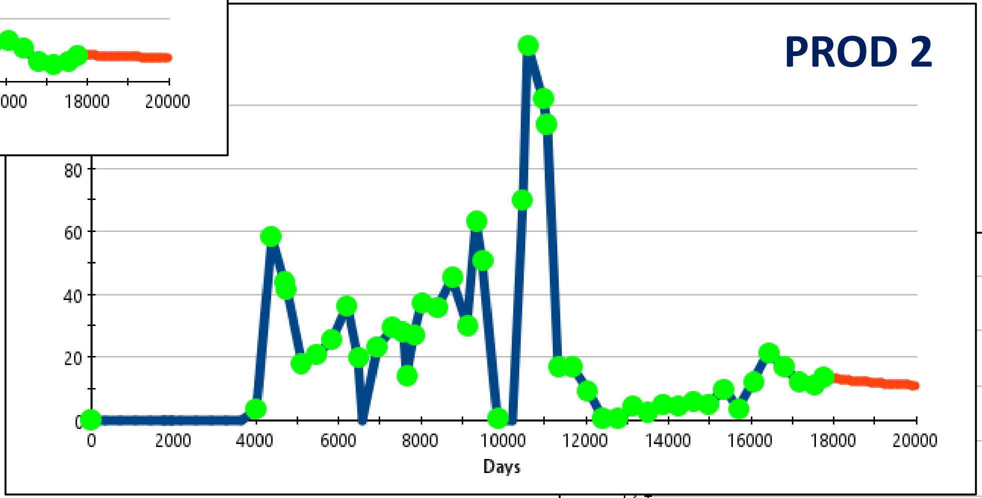
- Correlate historical production to features (K, phi, dP, Sats,…) in well drainage regions of the flow model.

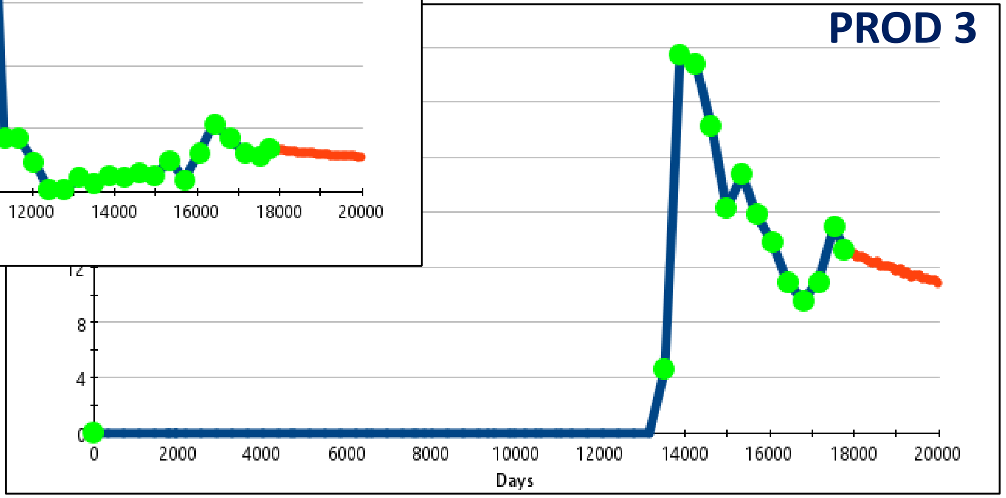


Forecasting Base Case - Wells

- Each existing producer has a unique forecast







Summary Streamline-Based Surveillance

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1. Dynamic pattern metrics
   - Flow-based Well Allocation Factors (WAFs)
   - WAF connection map (FPMap)
   - Injection Efficiency
2. New well rate targets to promote sweep and reduce cycling
3. ROIP from dynamic pattern material balance
4. Rapid forecasting
   - No Further Action (NFA) scenario
   - New well rate targets
   - Shut-in wells, reactivate wells, producer-injector conversion

Mature Field Management Example

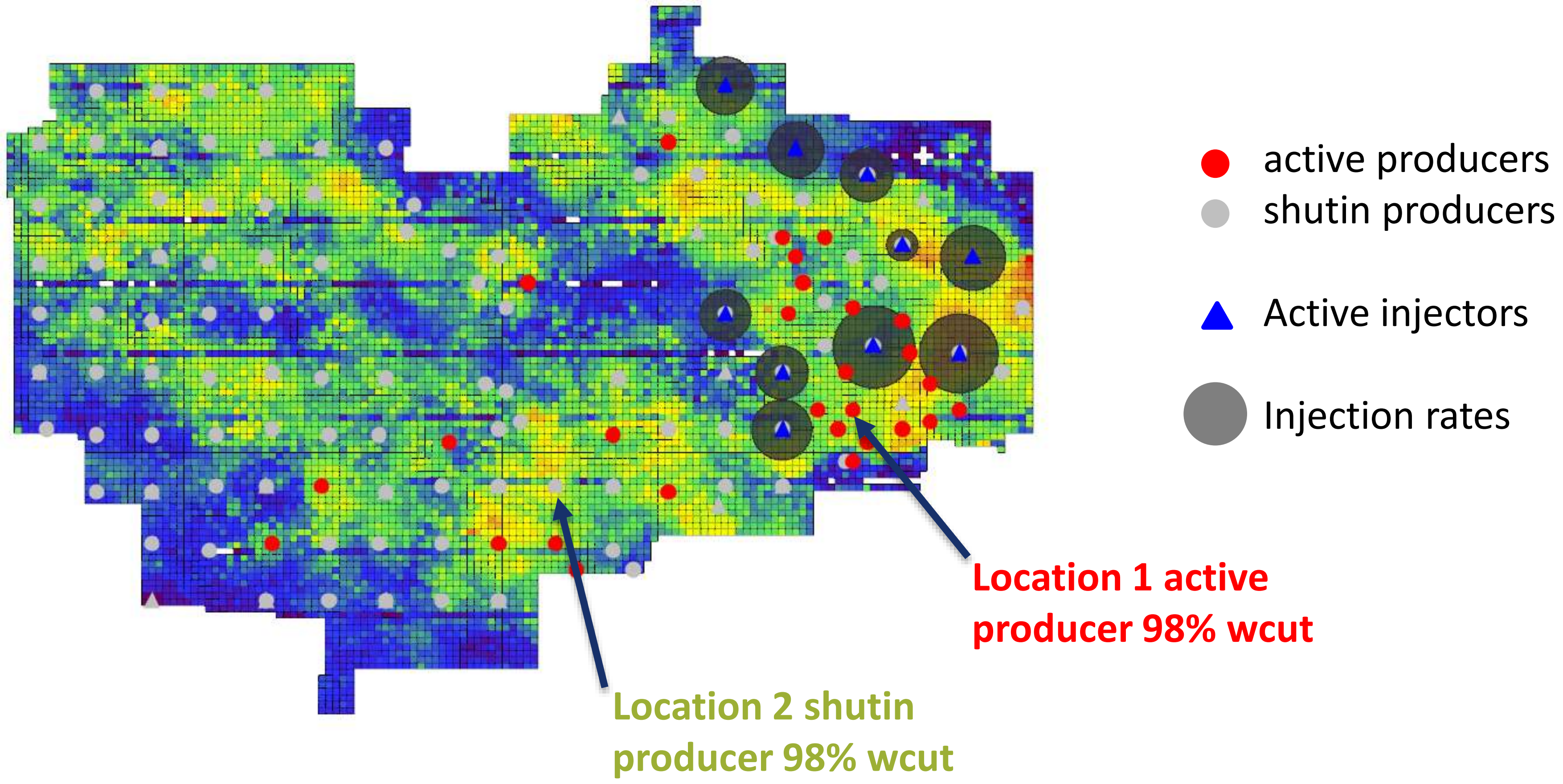
Improving Flood Performance

- Improvement strategies include:
  - Pattern realignment through rate changes
  - Reactivations, shut-ins, producer-injector conversions
  - Conformance treatments*
  - Polymer, surfactant, CO2, or solvent flooding*
  - Water quality*
  - Production gathering optimizations*
  - New producers*

  *beyond a surveillance model

- Forecast strategies prior to implementation:
  - Flow-based pattern surveillance
  - Reservoir flow simulation

Producer – Injector Conversions



Producer – Injector Conversions

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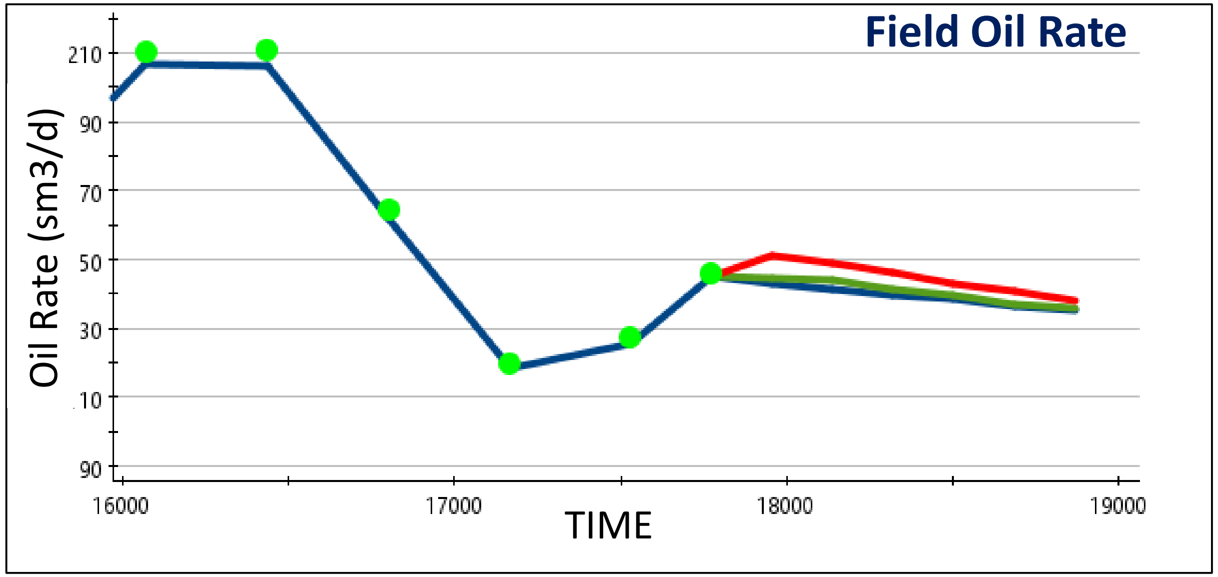
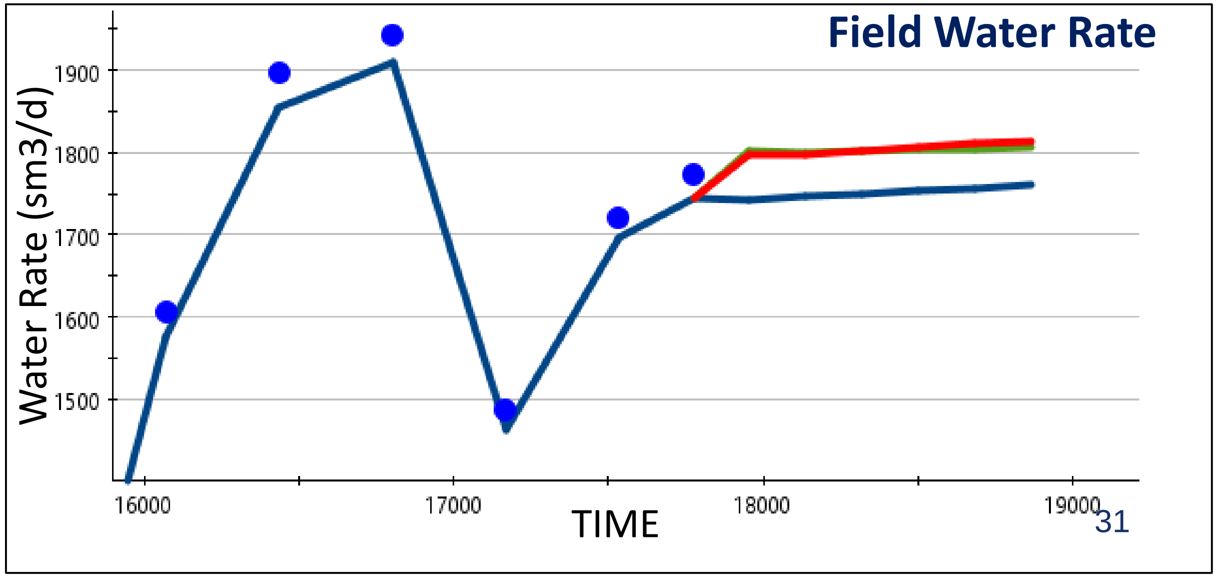
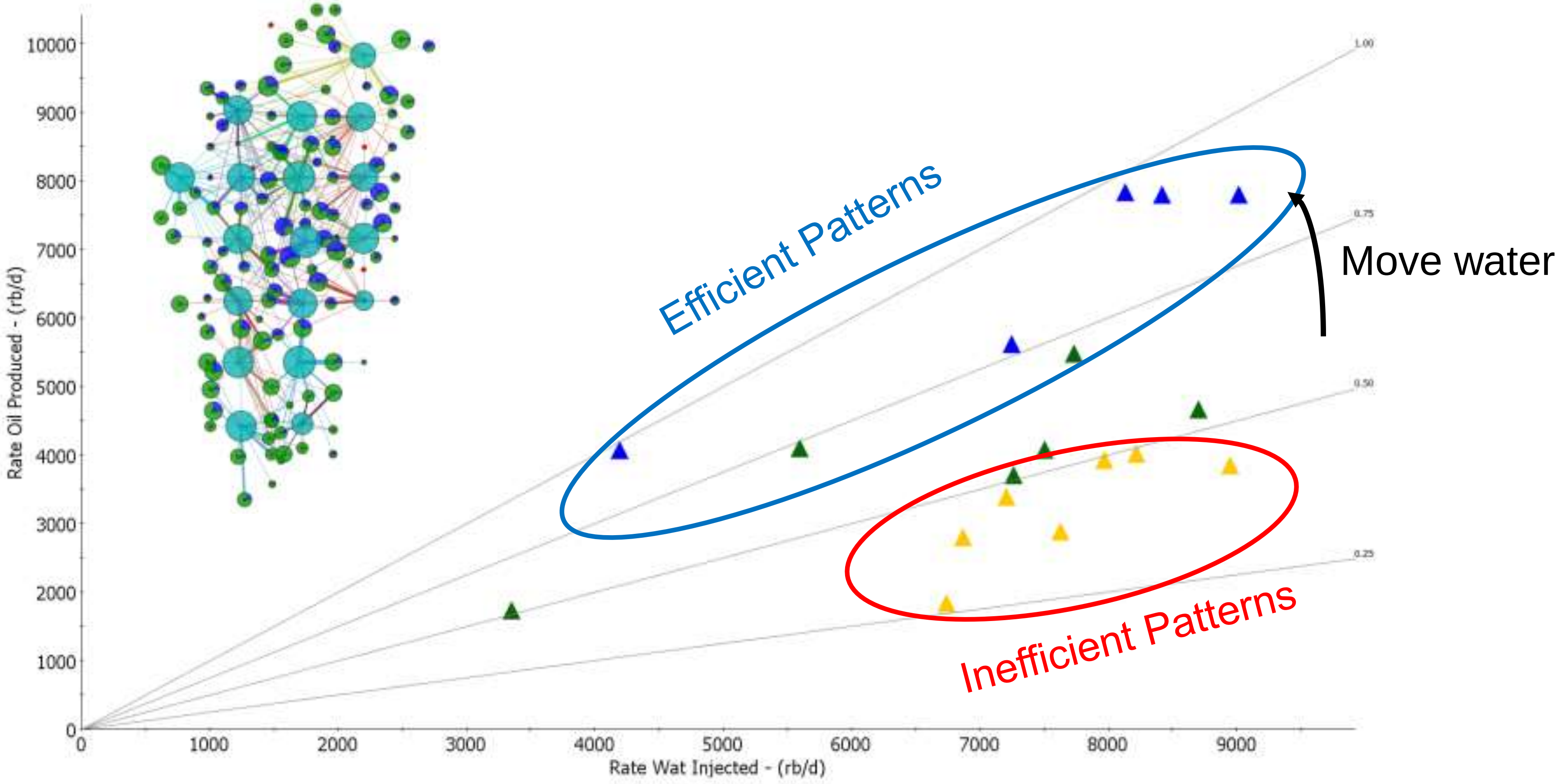
- Convert a watered-out producer to injection
  - Location 1 (+10 m3/d oil, +75 m3/d water)
  - Location 2 (+1 m3/d oil, +75 m3/d water)
  - Base case



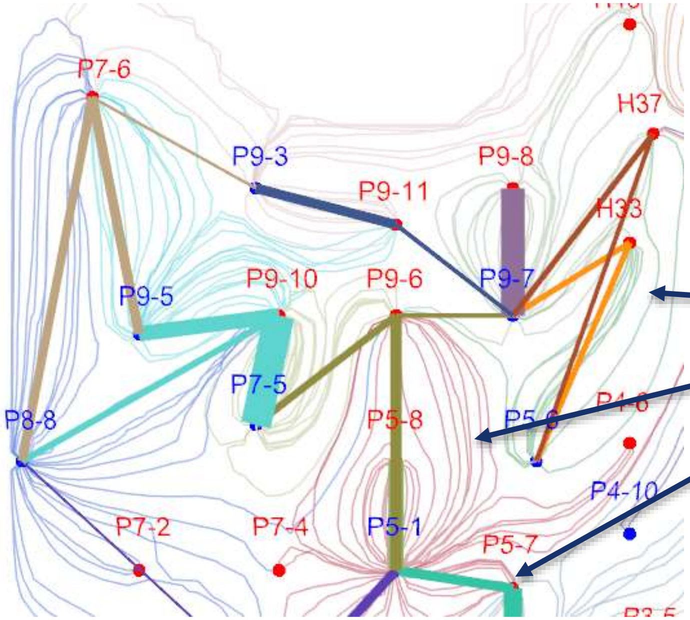


Improve Flood Efficiency



Improving Flood Efficiency

- 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.
- Intelligent well rate targets => 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"

Improve Flood Efficiency with Rate Targets

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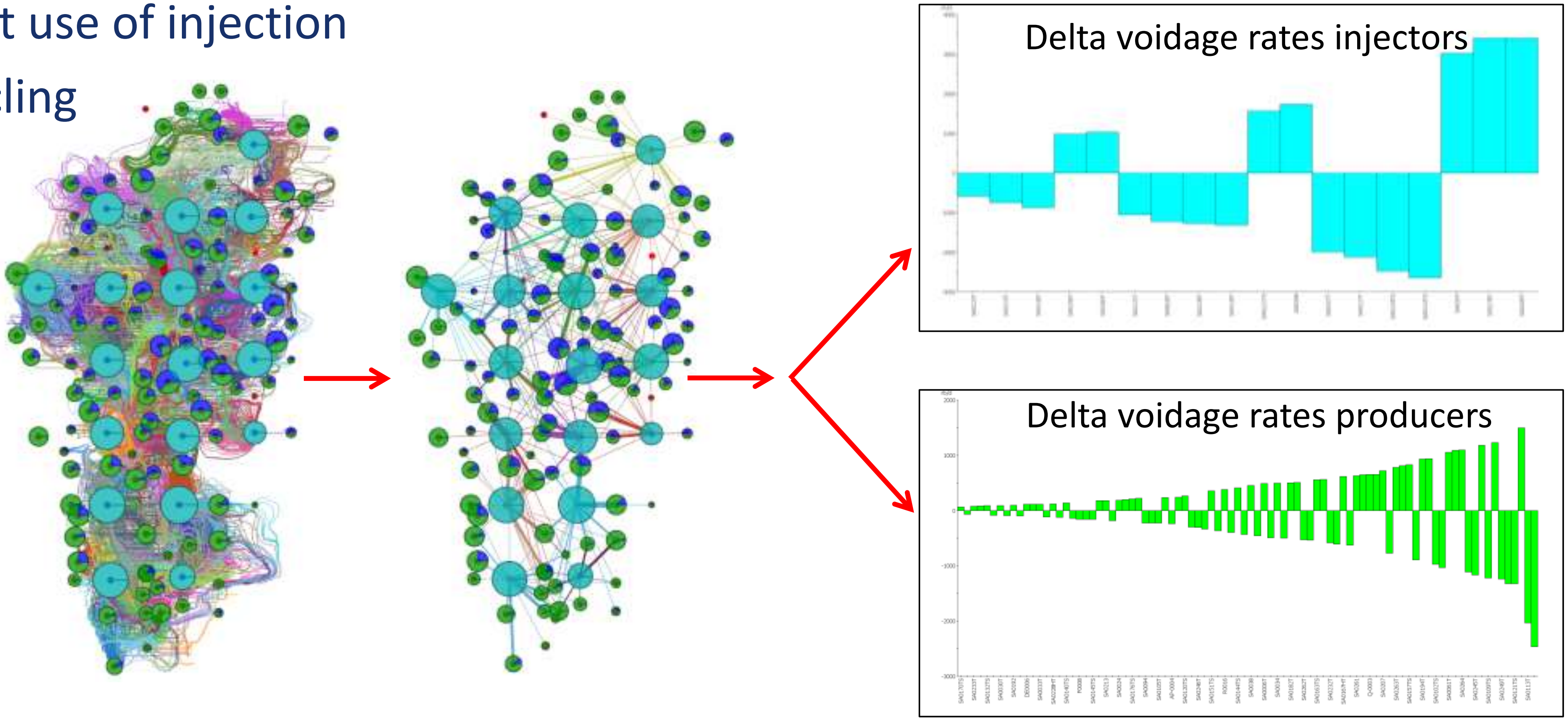
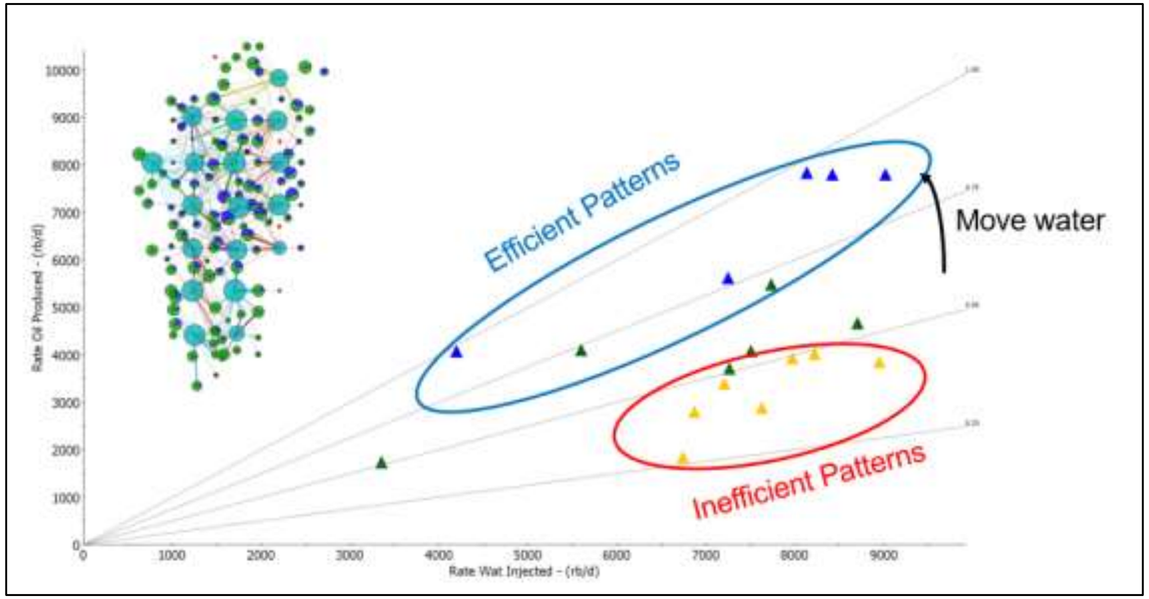
- FPmap + constraints = new rates
- Promote efficient use of injection
- Demote fluid cycling
- SPE84080-PA



Pattern Realignment with New Well Rates

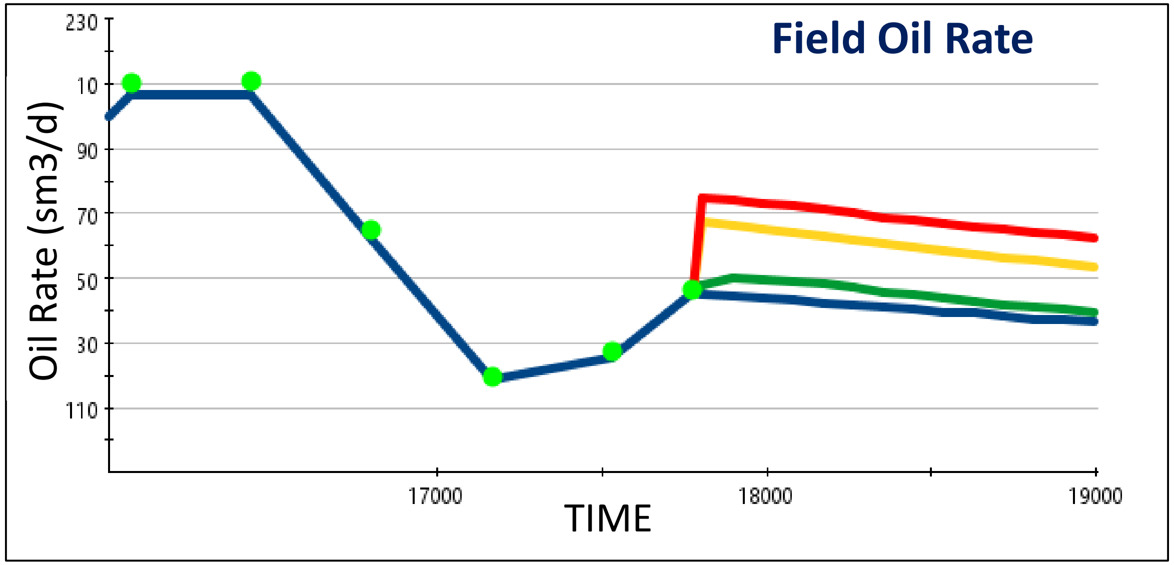
- Field constraints
  - Redistribute field water injection
  - Increase injection

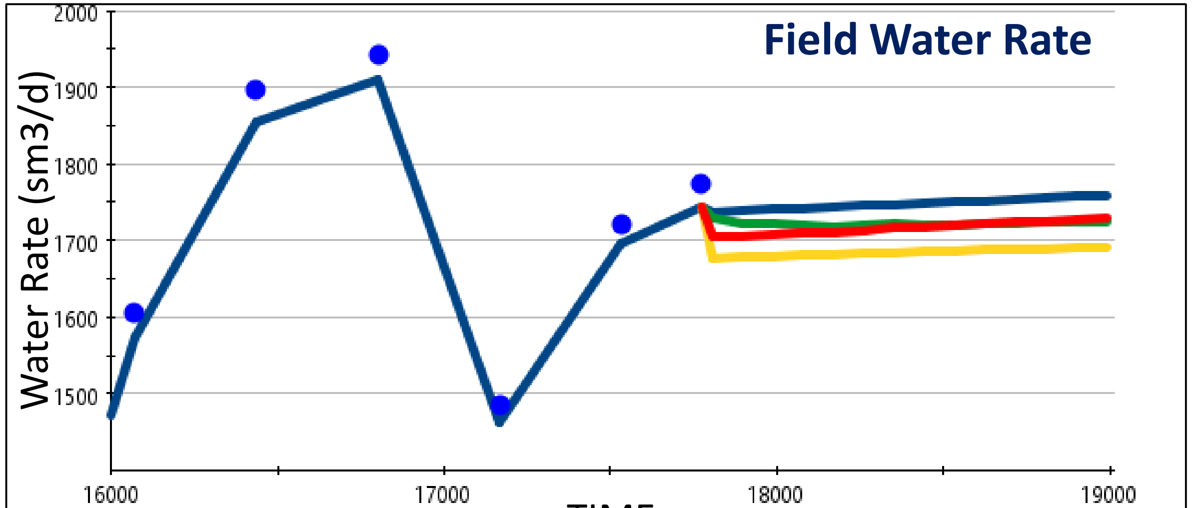


- Well constraints and strategies
  - Update both injection and production targets
  - Update injection targets, cutback on poor producers
  - Update injection targets only

Forecasting New Rates (without flow simulation)

- Redistribute field water injection rate of 1800 m3/d
  - **Update both injection and production targets**
  - **Update injection targets, cutback poor producers**
  - **Update injection targets only**
  - **Base case**





Surveillance Case Studies: Improvements through Well Rate Targets

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8th Tortonian Field, Austria, 2010/2012 – SPE-166393

- 3 injectors, 12 producers -> +35000 STB oil (incremental not accelerated) over 2.5 years

Tar 2 Fault Block Wilmington Field, USA, 2019 – SPE-195372

- Rate changes at 12 injectors, 10 producers -> 20% to 2% annual oil decline rate

Corcobo Field, Argentina, 2019 – 7th Congreso Producción y Desarrollo de Reservas

- Rate changes at 28 producers, 15 injectors -> 16% to 0% annual oil decline rate

Hormiguero Nantu M1, Ecuador, 2015 – SPE-177145

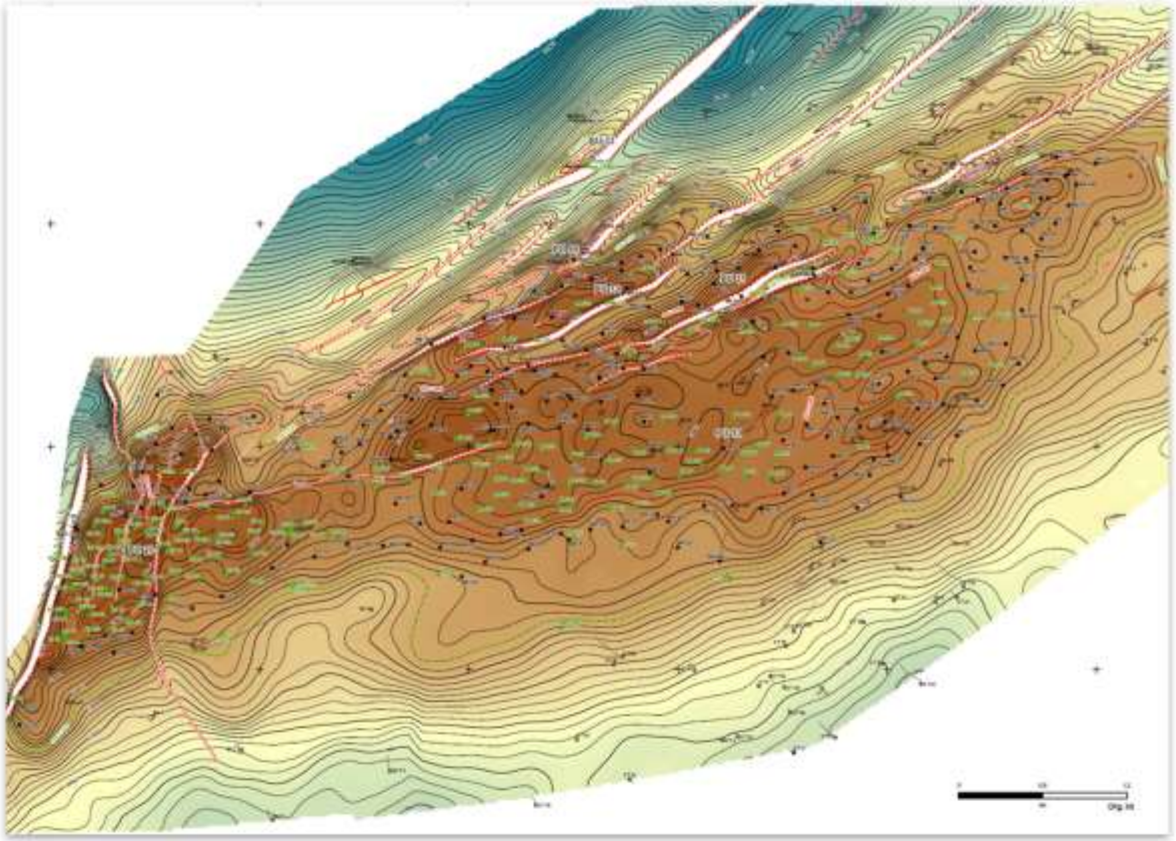
- Used streamlines to quantify well-pair connections to balance 2 injectors.
- From 2012-2015 waterflood optimization improved RF from 19% to 32%

16th Tortonian Horizon , Austria, 2022 – SPE-209679

- Rate changes to +70 producers and +12 injectors
- +3% increase in annual oil production for a 98% wcut field, reduced water production

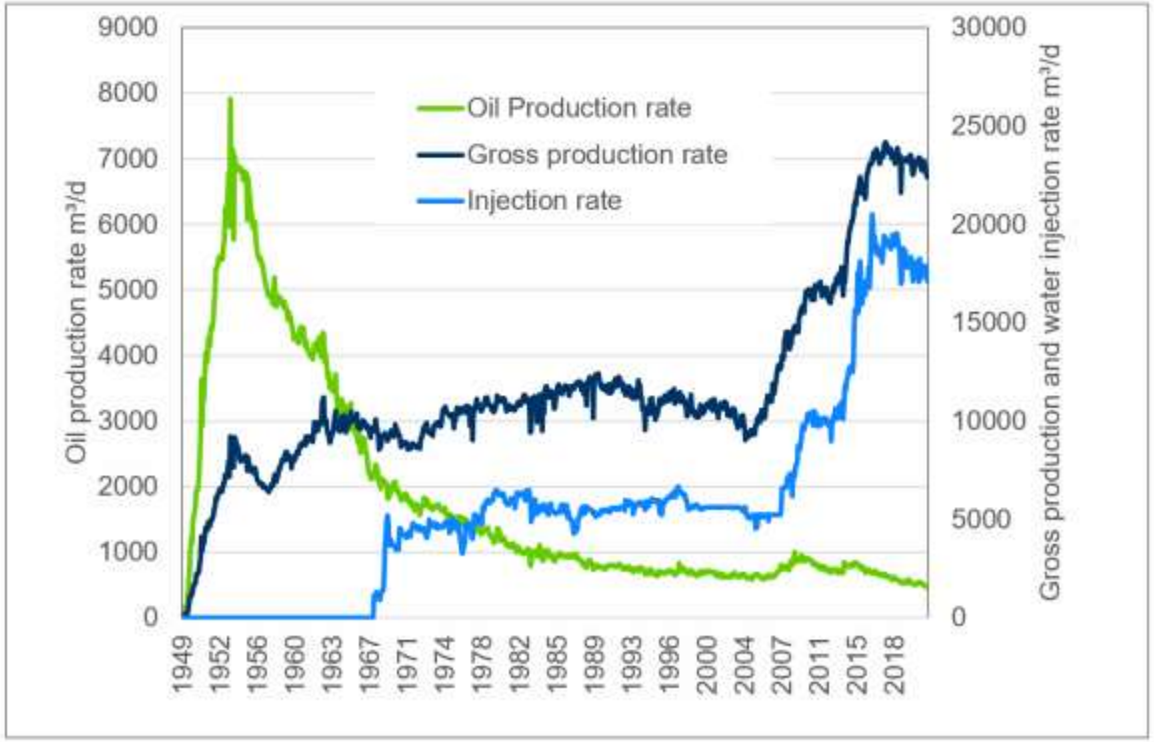
Introduction to 16.TH

- Part of Matzen field located 25km north-east of Vienna
- Marine Environment, Onlap transgressive layering
- High poro-perm (~27%, ~1 Darcy)
- Laterally extensive (50km2) with varying thickness (1-70m)
- Two asymmetric anticlines
- Considerable faulting separating multiple reservoir units
- Contacts in the main reservoir unit, 216-10, saturated oil
  - Initial OWC at -1490m TVDss
  - Initial GOC at -1455m TVDss



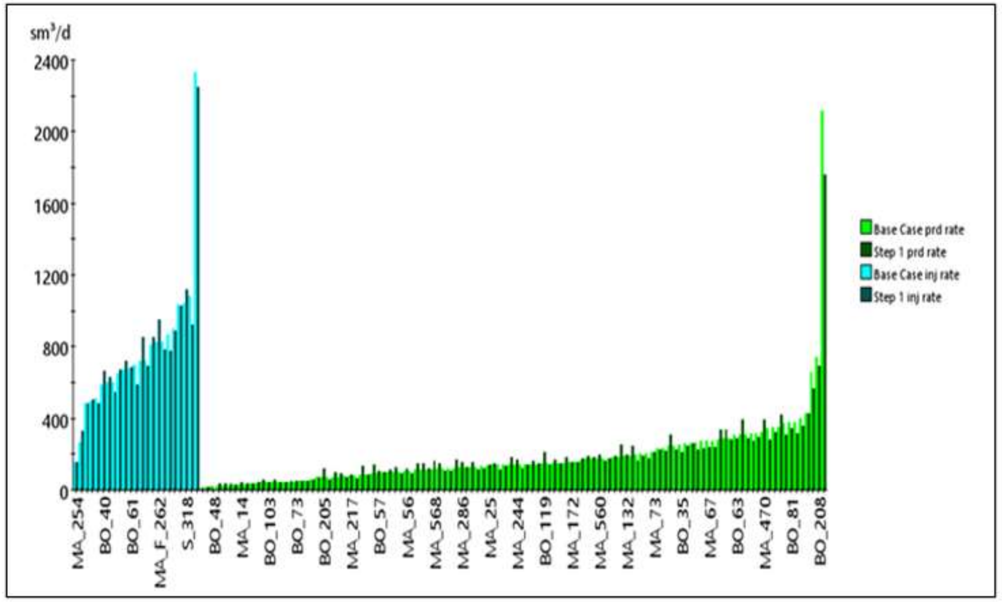
16.TH Characterisation & History

- The initial pressure was 160 bar
  - 25°API & 5cP oil
- Production started in 1949
- Water injection started in 1967, stabilizing pressure at ~120 bar
- Several development projects have taken place
  - Increasing well count, gross rate, injection rate and oil rate
- At present, 176 of the 427 total wells remain active
- All producing under artificial lift
  - **74 SRP's, 41 ESP's, 32 GL**



Review Individual Well Targets

- Model derived target rates are then reviewed individually from both a reservoir and completion perspective.



- Generally, from the reservoir side most target rates were achievable with exceptions:
  - Poor inflow – evident from the low dynamic fluid level during operation but high static fluid level
  - Gas coning wells – where historic increases saw a tendency for large GOR increases
- Therefore any well with target rates with the issues above, were disregarded

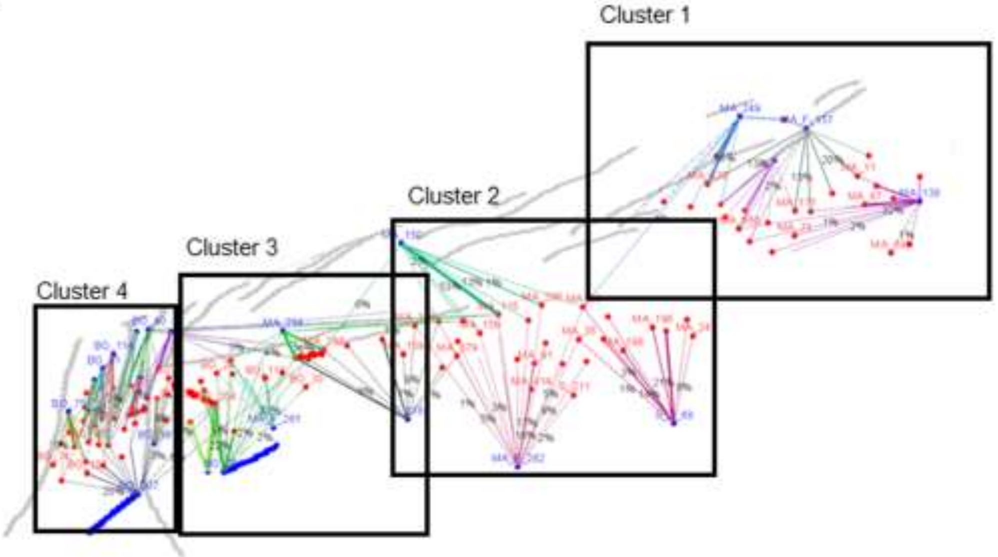
Modelling & Data Analysis - Uncertainty

- There were two major drivers influencing the modelling approach
  - Faulting – uncertainty of transmissibilities
  - Lower sands – disconnected nature
- Wells producing from the lower sand had their perforations and volumes removed
- Multiple models were therefore setup, ranging fault transmissibilities to check for consistency in derived rate targets
- It was found that across all transmissibilities, target rate directions were generally the same and only magnitude changed.
- This gave confidence in taking one model moving forward to derive rate targets.

	Target Rate Change of Model		
Well Name	Fault Trans 0	Fault Trans 0.5	Fault Trans 1
BO_101	16.26	17.15	17.08
BO_102	7.95	6.66	6.76
BO_103	-4.45	-4.45	-4.45
BO_104	1.35	-3.72	-3.62
BO_112	-30.07	-30.07	-30.07
BO_118	10.06	10.95	10.90
BO_119	-46.83	-45.39	-45.39
BO_120	-59.50	-59.50	-59.50
BO_14	12.77	13.56	13.48
BO_151	11.96	12.95	12.88
BO_152	17.31	18.25	18.22
BO_153	13.06	13.10	13.20
BO_182	17.67	18.52	18.55
BO_201	-35.35	-35.35	-35.35
BO_202	-59.82	-58.95	-58.85
BO_204	16.65	16.88	16.93
BO_205	-84.24	-82.58	-82.72
BO_208	6.59	6.59	6.59
BO_209	-22.66	-34.42	-34.42
BO_23	2.48	0.54	0.54

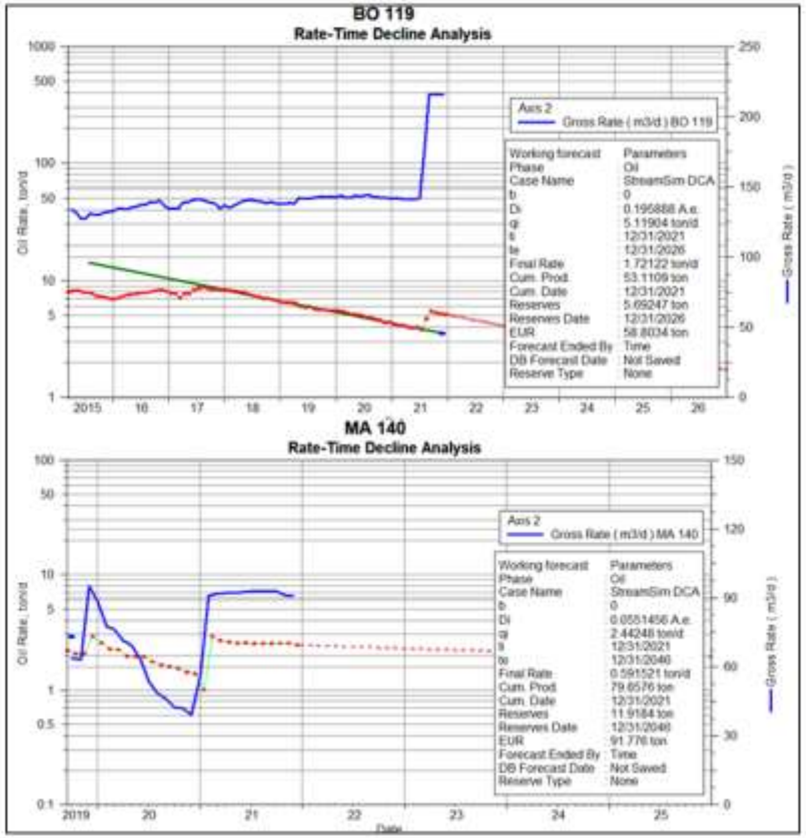
Finalised Model & Clustering

- To enable systematic implementation of target rates, the well changes were split by clear identification of well injector-producer pairs, as well as major geological features.
- Cluster 1 and 2 showed the most potential and had overall gross increases, cluster 3 had a large gross decrease contributing to the overall lower gross rate by end of year.
- Across the period of a year, the clusters rate changes were implemented systematically from cluster 1 to cluster 4.



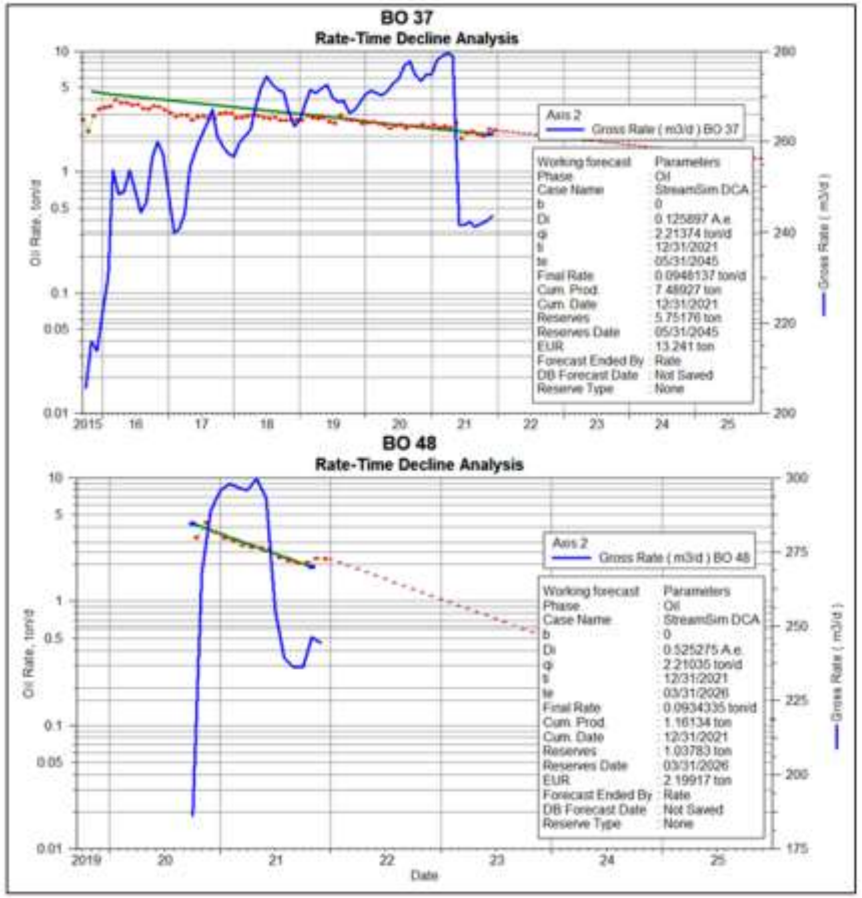
Expected Well Responses

- The more common responses were those seen in BO 119 and MA 140
  - Gross increases / decreases
  - Proportional oil increases / decreases
  - **Constant watercut** with rate changes
- These examples gives a feel of the varied responses across the wells.
- The full implementation of rate changes across 2021



Positive Well Responses

- A variety of responses on the wells were found
- BO 37 & BO 48 were great performing wells
  - Gross decreased (lower opex)
  - Oil increased
  - **Reduction in watercut**
- Likely due to a high degree of water cycling and high permeability streaks from injectors to producers



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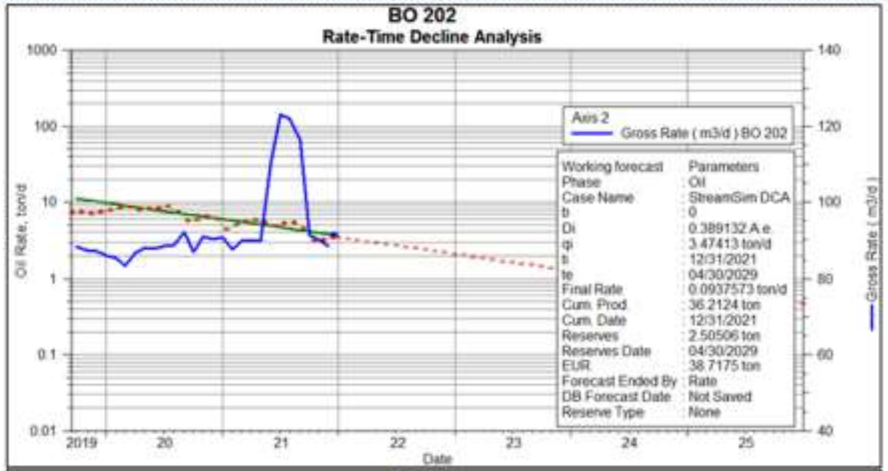
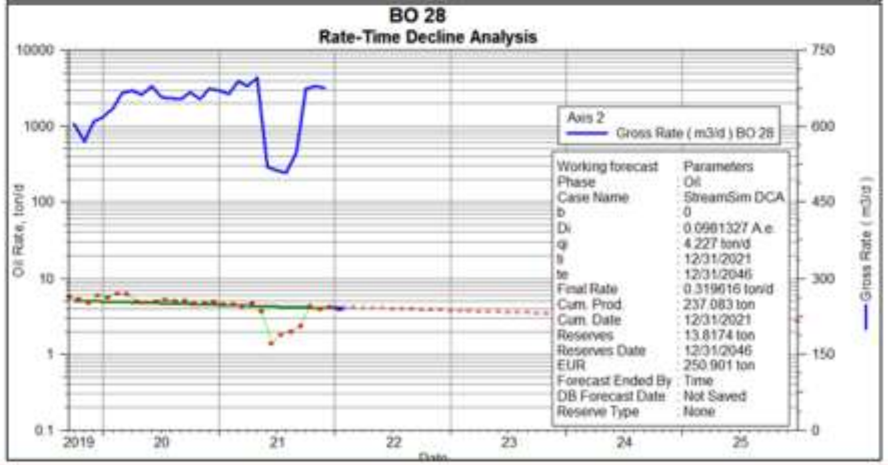
Negative Well Responses

- BO 202 had a poor response to the rate change
  - Gross was increased
  - Oil remained constant
  - **Increase in watercut**

- BO 28 also had a poor response
  - Gross decrease of ~30%
  - Oil decrease of ~70%
  - **Increase in watercut**

After a few months of poor performance, these wells were reverted to their original setting where fortunately historic performance was restored.



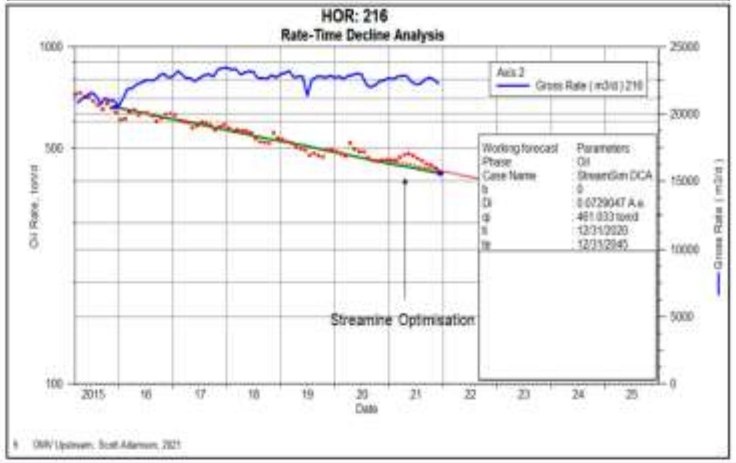


Results – Full Field

- The yearly liquid and injection rates fluctuated as the well changes were rolled out in their clusters, however across the year saw great returns

- The yearly performance resulted in:
  - **+3 %** on **annual produced volume**
  - **~35,000 barrels incremental**
  - **Net reduction** in **liquid injected** and **produced**

- Observation of the performance in line with recent history, demonstrates the positive impact on production from the low-cost implementation of the streamline derived flood optimization measures



SL-Based Surveillance Summary

- SL-based surveillance model
  - 3D flow model
  - Requires well locations, rates, 1st order geology
  - Computationally light, data-driven model

- Powerful per pattern metrics
  - Flow-based WAFs (FPmap)
  - Pattern efficiencies (IE-Plot)
  - ROIP distribution
  - Rate targets that promote sweep and demote cycling

- Rapid forecasting
  - Test rate targets and strategies to realign flood
  - Rank producer-injector conversion candidates
  - Rank shut-ins and reactivations of existing wells

Further Reading

- “*Using Streamline-Derived Injection Efficiencies for Improved Waterflood Management*” (SPE84080-PA)
- "*Revisiting Reservoir Flood-Surveillance Methods Using Streamlines*” (SPE95402-PA)
- "*Experiences With an Efficient Rate-Management Approach for the 8th Tortonian Reservoir in the Vienna Basin*” (SPE166393-PA)
- “A Successful Peripheral Water Injection in a Weak-Edge Aquifer Oilfield, Oriente Basin, Ecuador” (SPE177145-MS)
- Oriente Basin, Ecuador“*Material Balance Applied to Dynamic Reservoir-Surveillance Patterns*” (SPE185713-PA)
- “*Improved Water Efficiency in the Wilmington Field Using Streamline-Based Surveillance*” (SPE195372-MS)
- “Implementation of Streamline Derived Rate Targets Improved Oil Production of Mature Field (SPE209679-MS)

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