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Distinguished Lecturer Program

Field Surveillance & Management Using Streamlines

Marco R. Thiele

Streamsim Technologies / Stanford University

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Distinguished Lecturer Program

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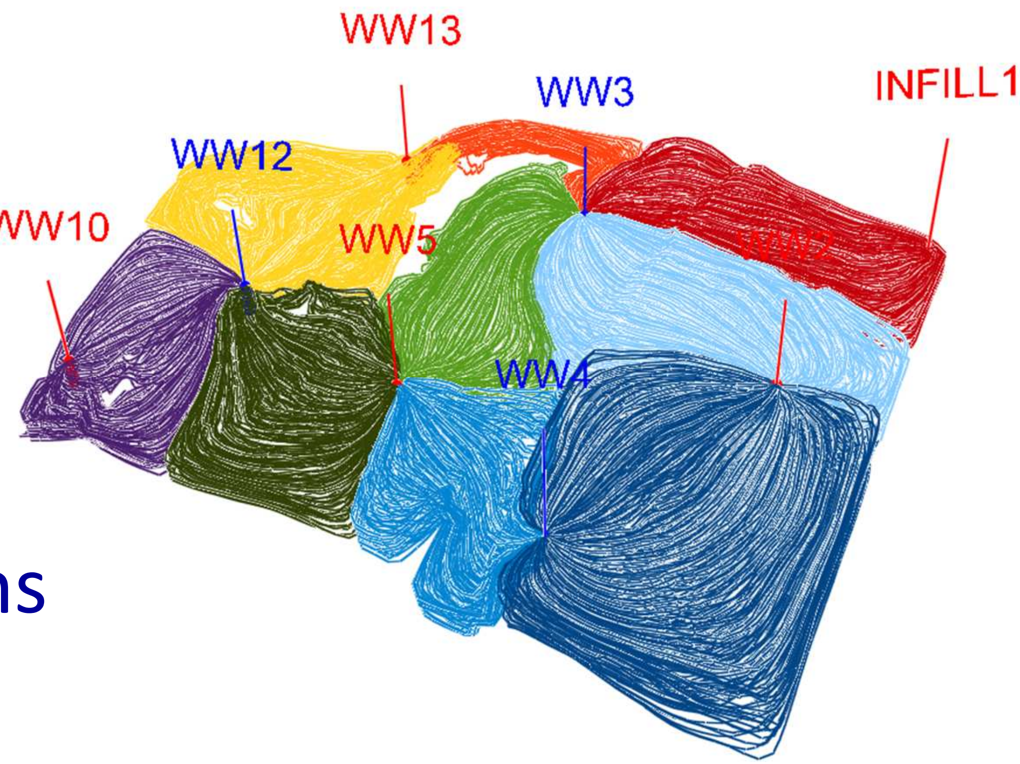
Outline

- The basics of streamline simulation
- Flood surveillance
- Managing floods
- Other SL applications
- Summary & conclusions



Streamline (SL) Simulation

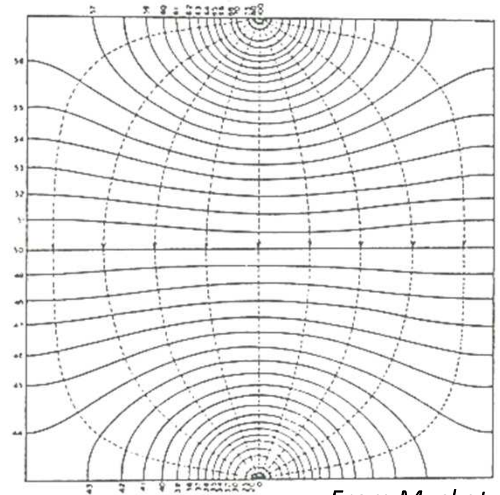
- An alternative *numerical* modeling tool.
  - Complimentary to finite-volume approaches. Use
    - SL→for systems at or near voidage replacement.
    - FV→dominated by absolute pressure/diffusive forces.
  - "Simpler and faster" for the right problems.

- Excellent at capturing reservoir connectivity.
  - Quantify interaction of geology, well locations and rates.

- New metrics.
  - New insight and data for managing mature fields.
  - Powerful visual information and pattern performance metrics.

Streamlines' Long History in RE

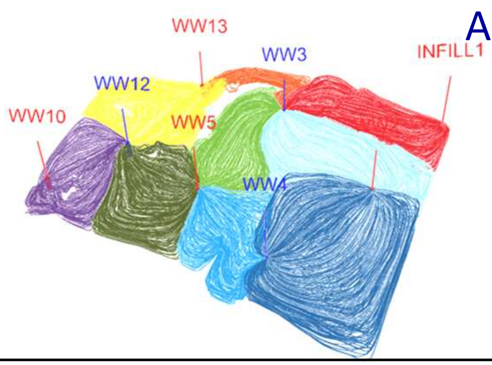
- 1930's—Muskat & Wyckoff
- 1950's—Fay & Pratts
- 1960's—Morel-Seytoux, Higgins & Leighton
- 1970's—LeBlanc & Caudle, Martin & Wegner, Bommer & Schechter,
- 1980's—Lake et al., Emanuel et. al., Hewett & Behrens



From Muskat

- 1990's to present—Modern SL Simulation

Arihara,Batycky,Behrens,Blunt, Bratvedt, Cheng, Crane, Datta-Gupta, Di Donato, Emanuel, Gautier, Gerritsen, Grinestaff, Jessen, King, Mallison, Milliken, Orr, Osako, Prevost, Thiele…and many more.

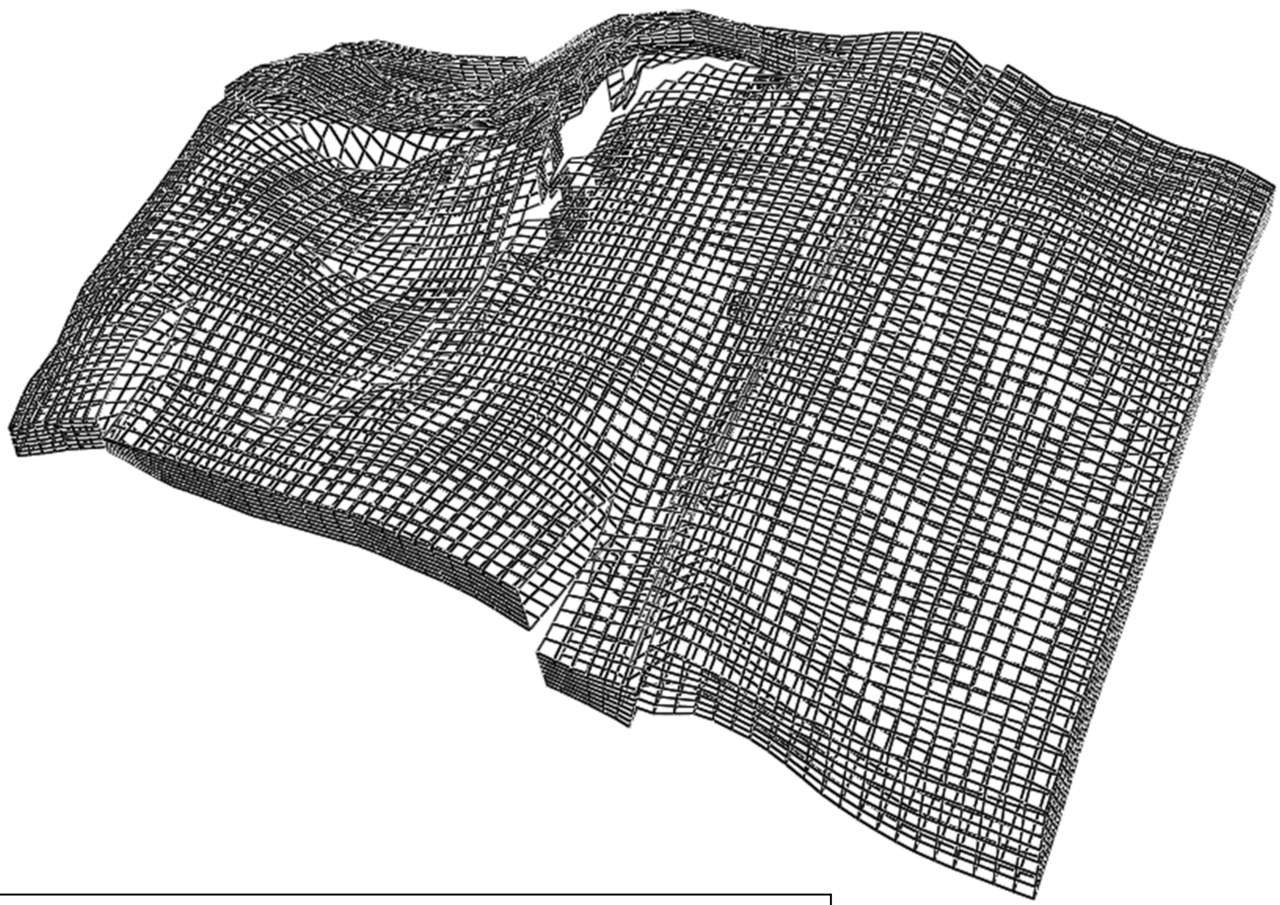


Modern SL Simulation

- Streamlines traced in 3D
  - Previously 2D, homogenous domains only.
- Streamlines are updated in time.
  - Previously steady-state only; fixed well locations & rates for all times.
- Conservation eqs solved numerically along 1D SL's.
  - Previously analytical 1D solutions along fixed SL's.
- Included gravity using operator splitting.
  - Previously not accounted for since models were 2D.
- Account for fluid/rock compressibility.
  - Previously not accounted for since incompressible & steady state.

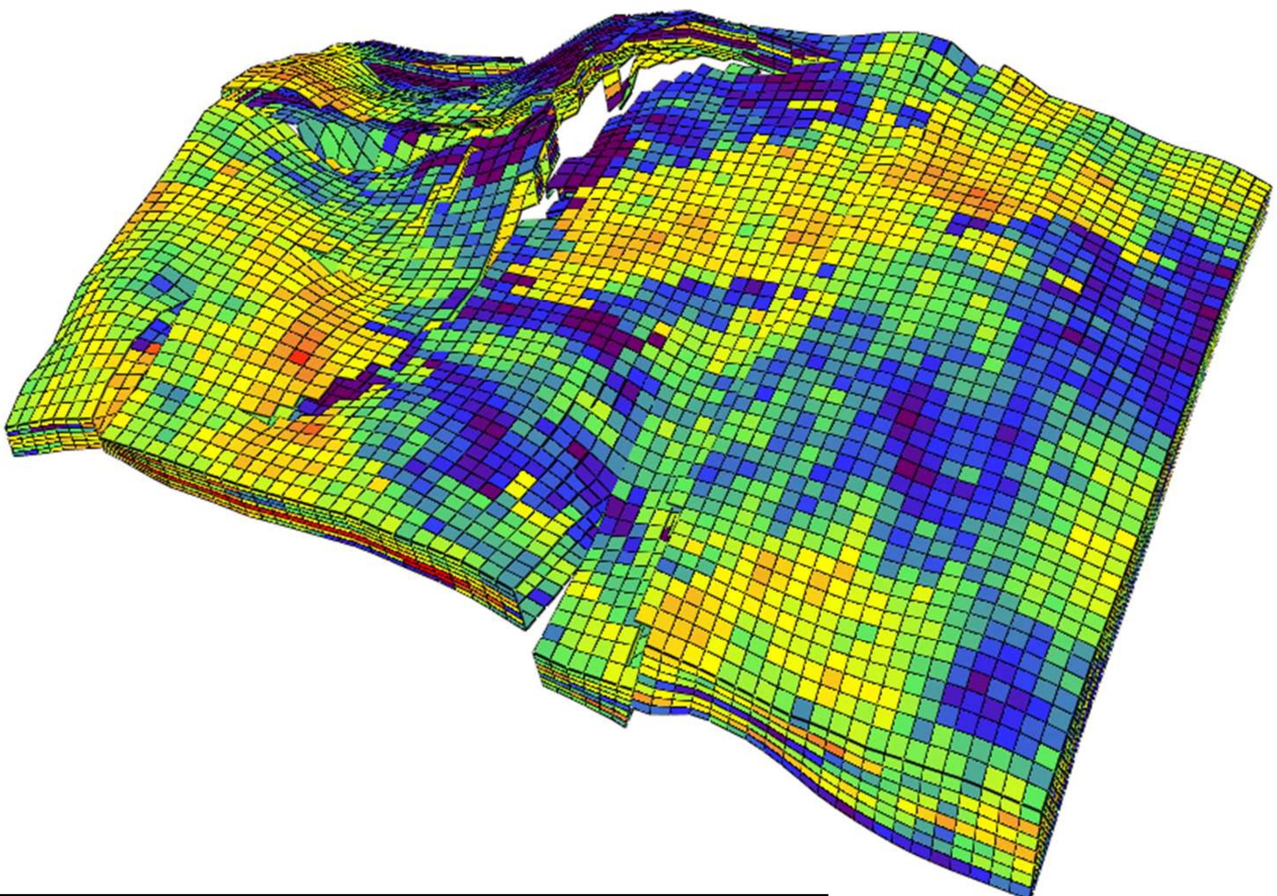
THE BASIC STEPS

The Static Grid



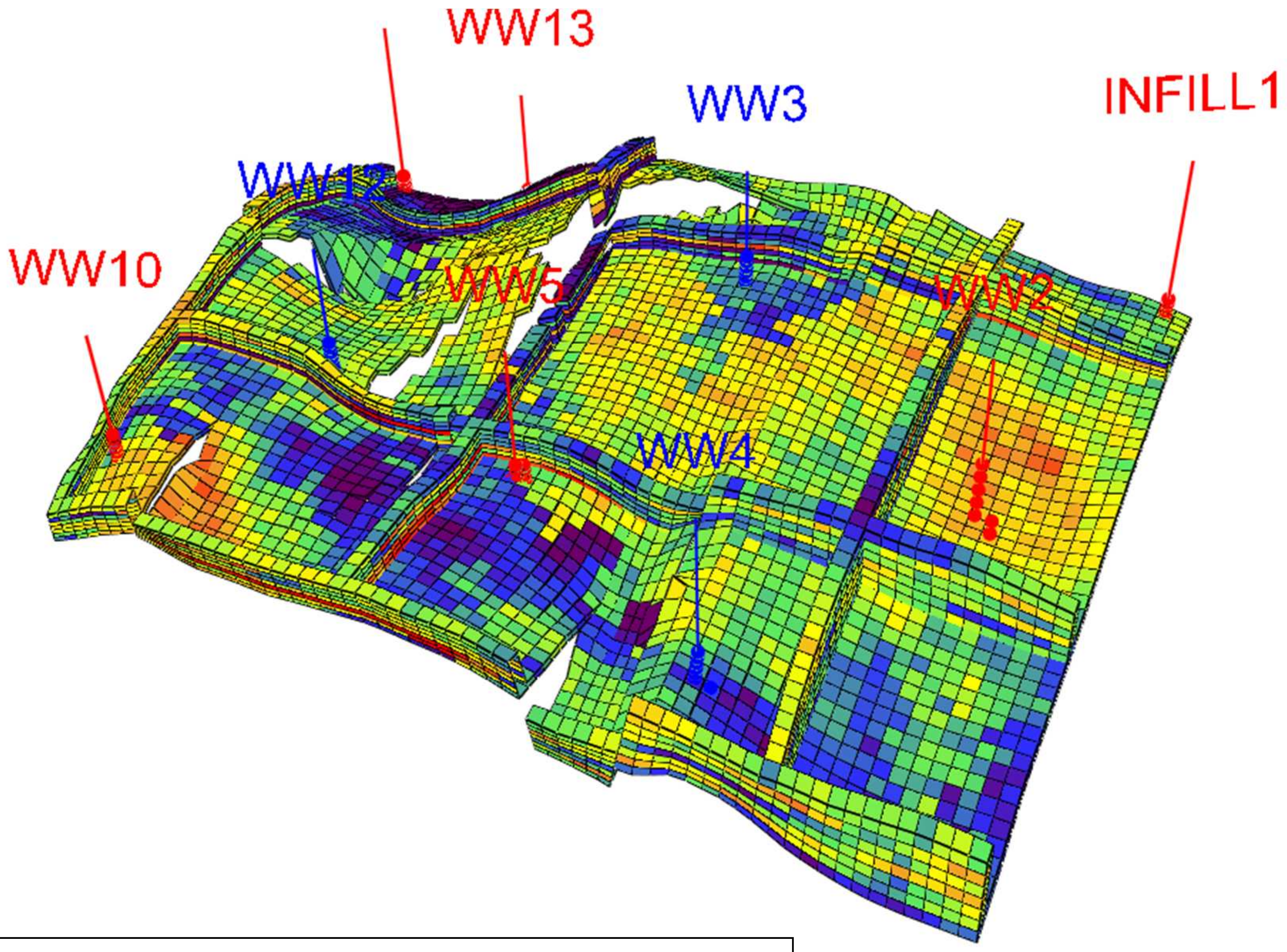
The mesh.

The Static Grid



The mesh + rock properties.

Wells



The mesh + rock properties + wells.

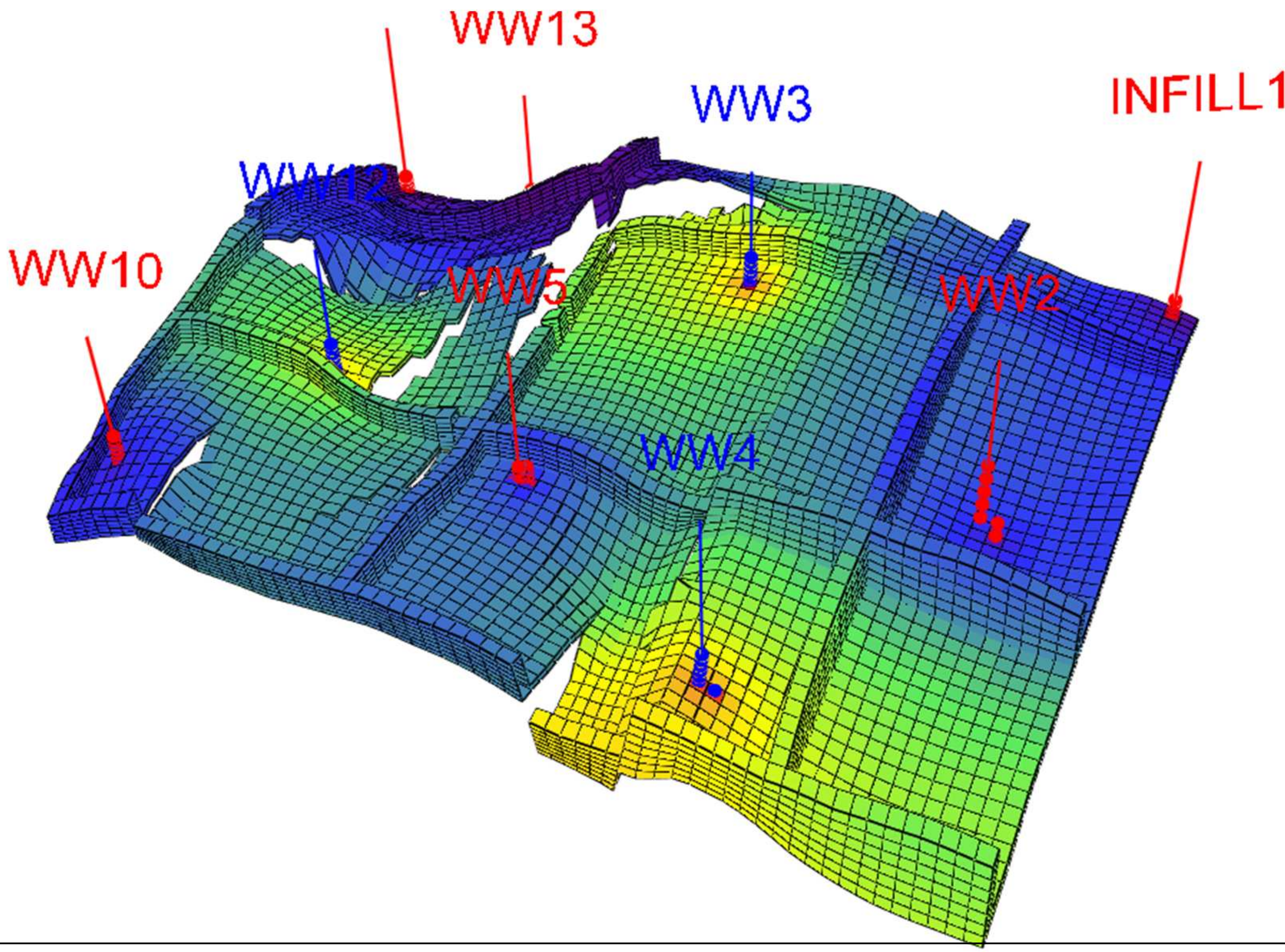
The Total Velocity Field

- *"A streamline is a line everywhere tangent to the velocity field."*

- Find the velocity field explicitly by:
  - Solving for pressure at the center of each cell
  - Use Darcy's Law to find the total velocity cell interfaces
  - Trace SLs (Pollock's method, explicit integration, etc…)

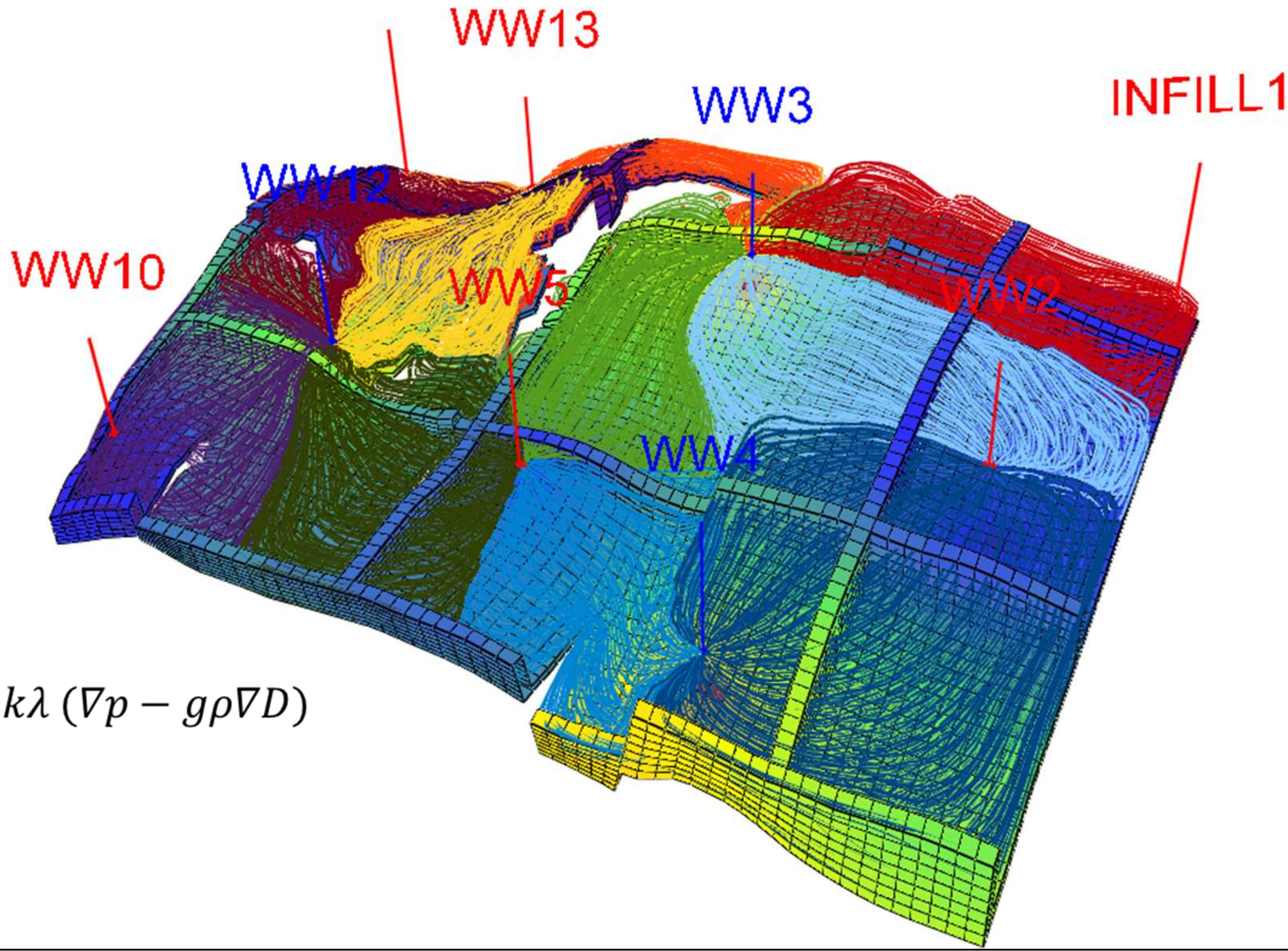
- SLs will normally start in a source (high P) and end in a sink (low P).

Pressure Distribution



Solve for pressure as in finite-difference simulation (Ax=b).

Tracing Streamlines



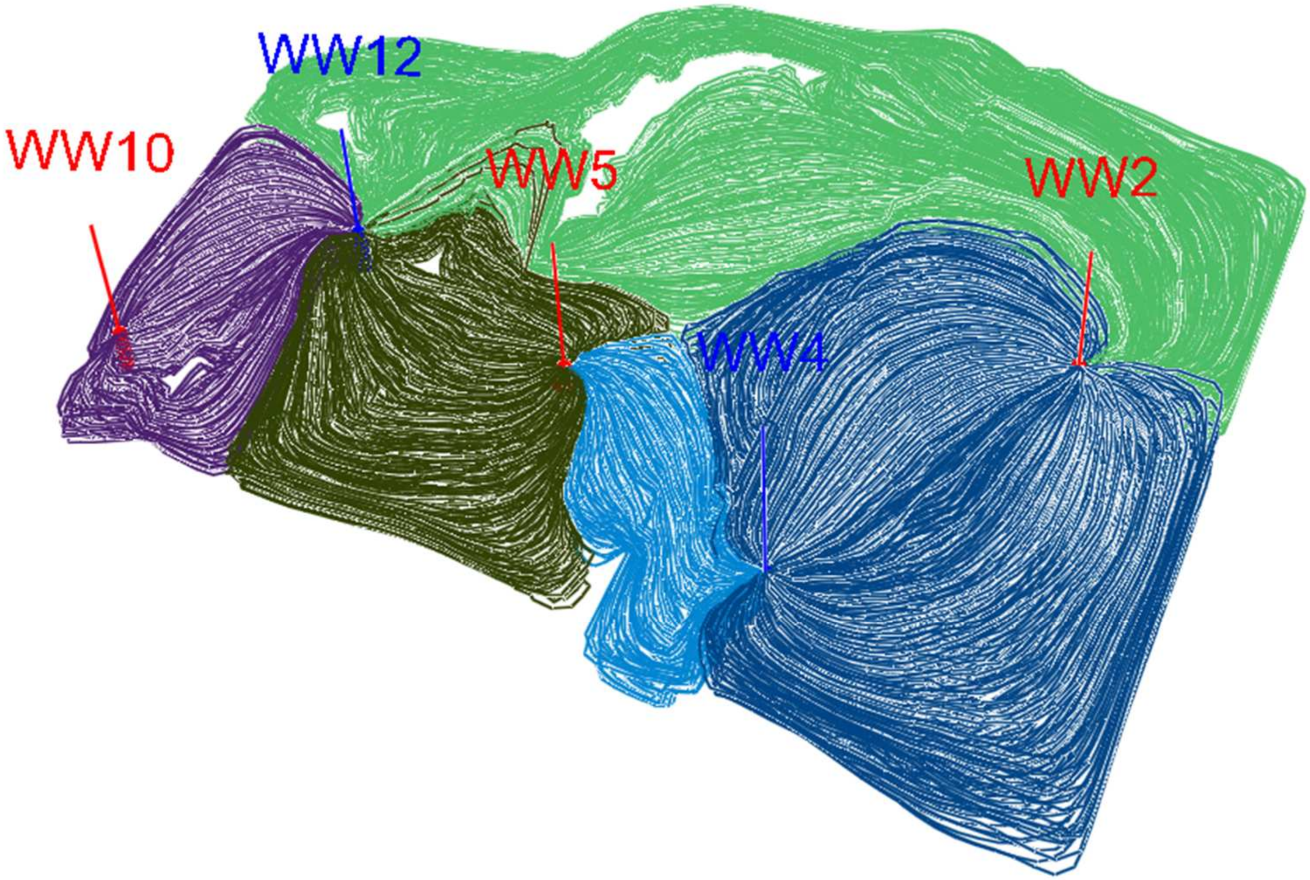
$$v = k\lambda\,(\nabla p - g\rho\nabla D)$$

Trace SLs using velocity field using pressure field + Darcy's Law.

SLs Change in Time

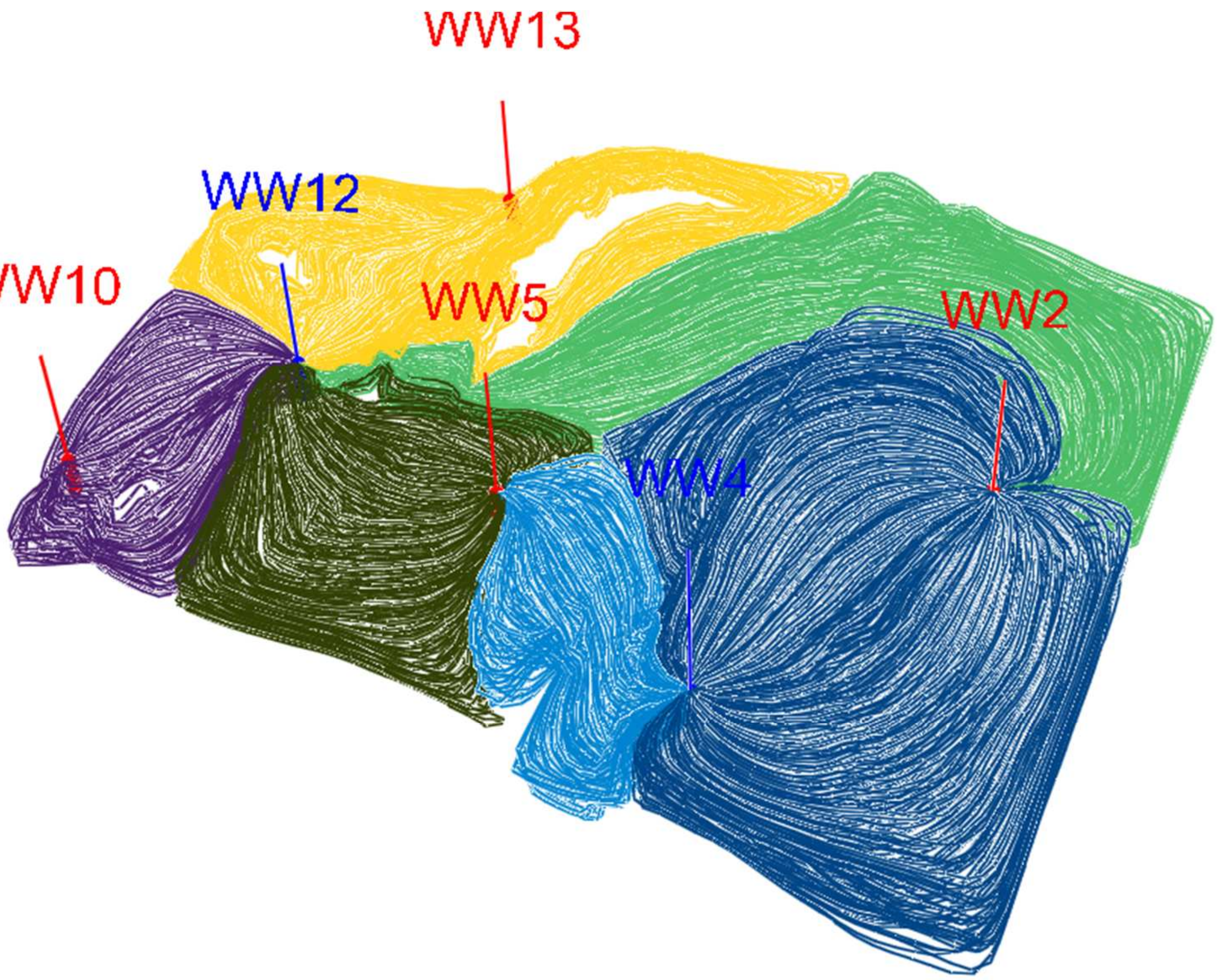
- As new wells come online or shut-in, the velocity field changes.
- As fluid distribution changes so will the pressure and velocity field.
- Account for changes of SL as a sequence of steady-state steps…
  - Assume the SLs geometry are fixed and valid for a period of time Δt.

Streamlines at t_1



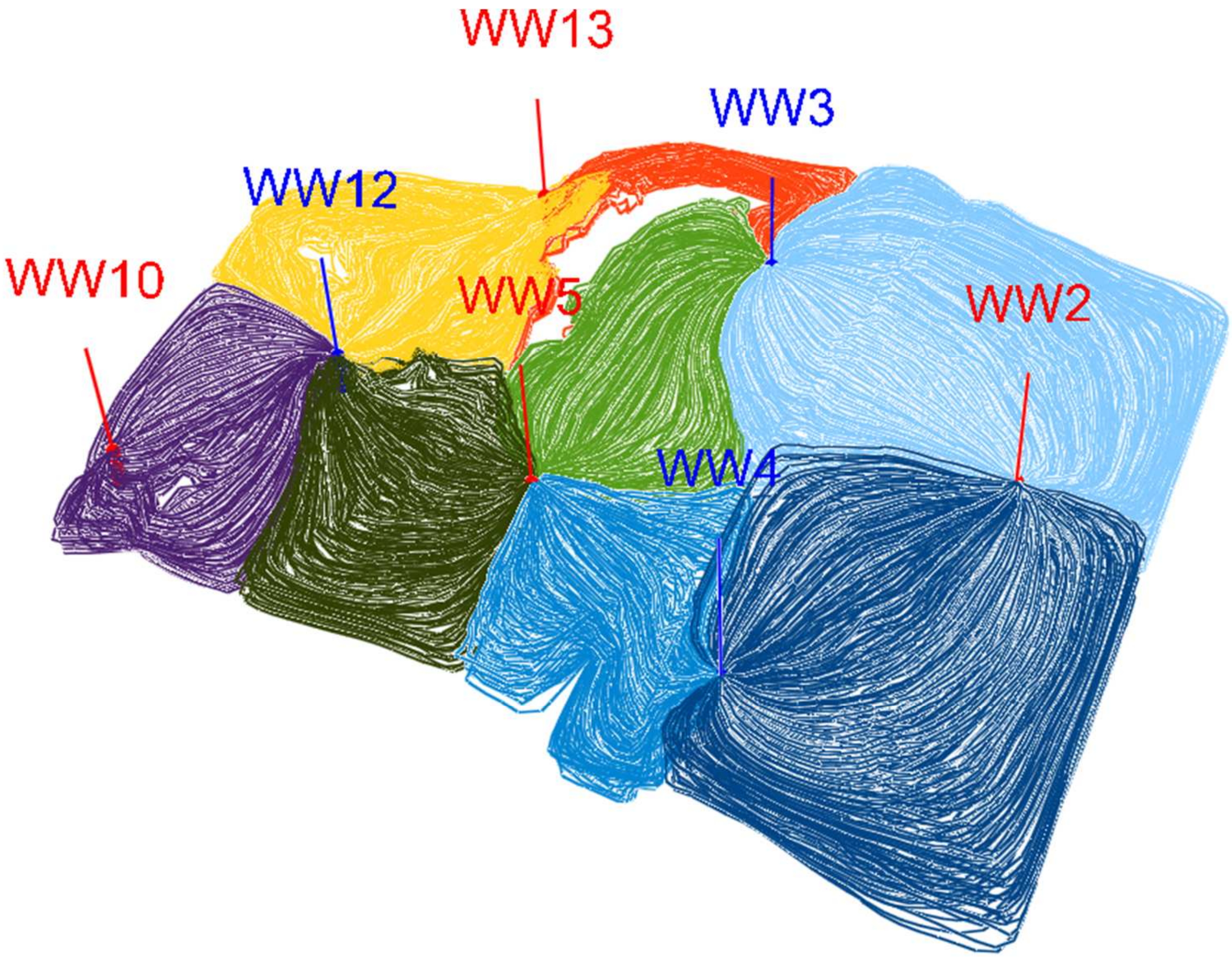
SLs change in time because of new wells and mobility changes.

Streamlines at t_2



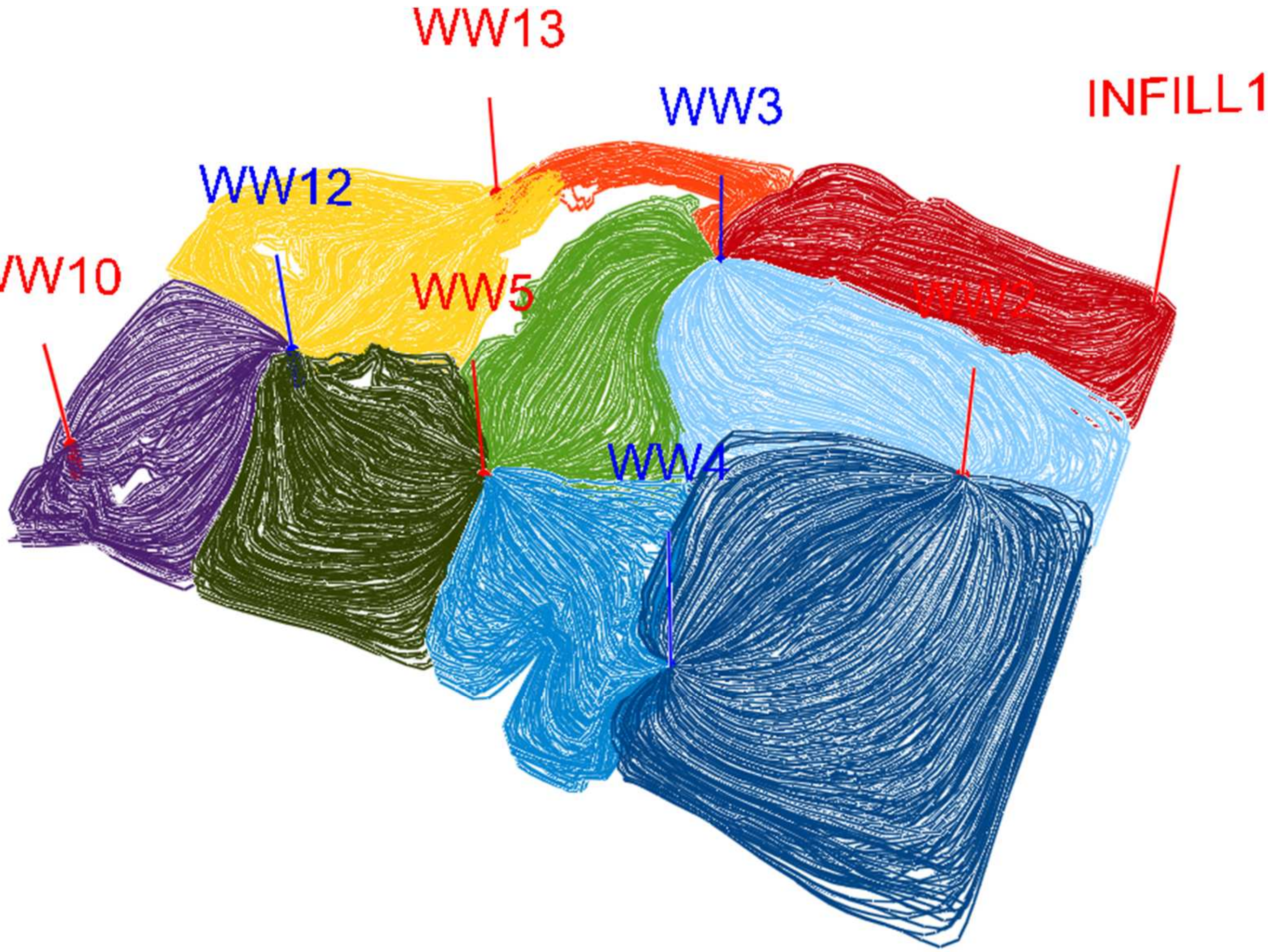
SL's change in time because of new wells and mobility changes.

Streamlines at t_3



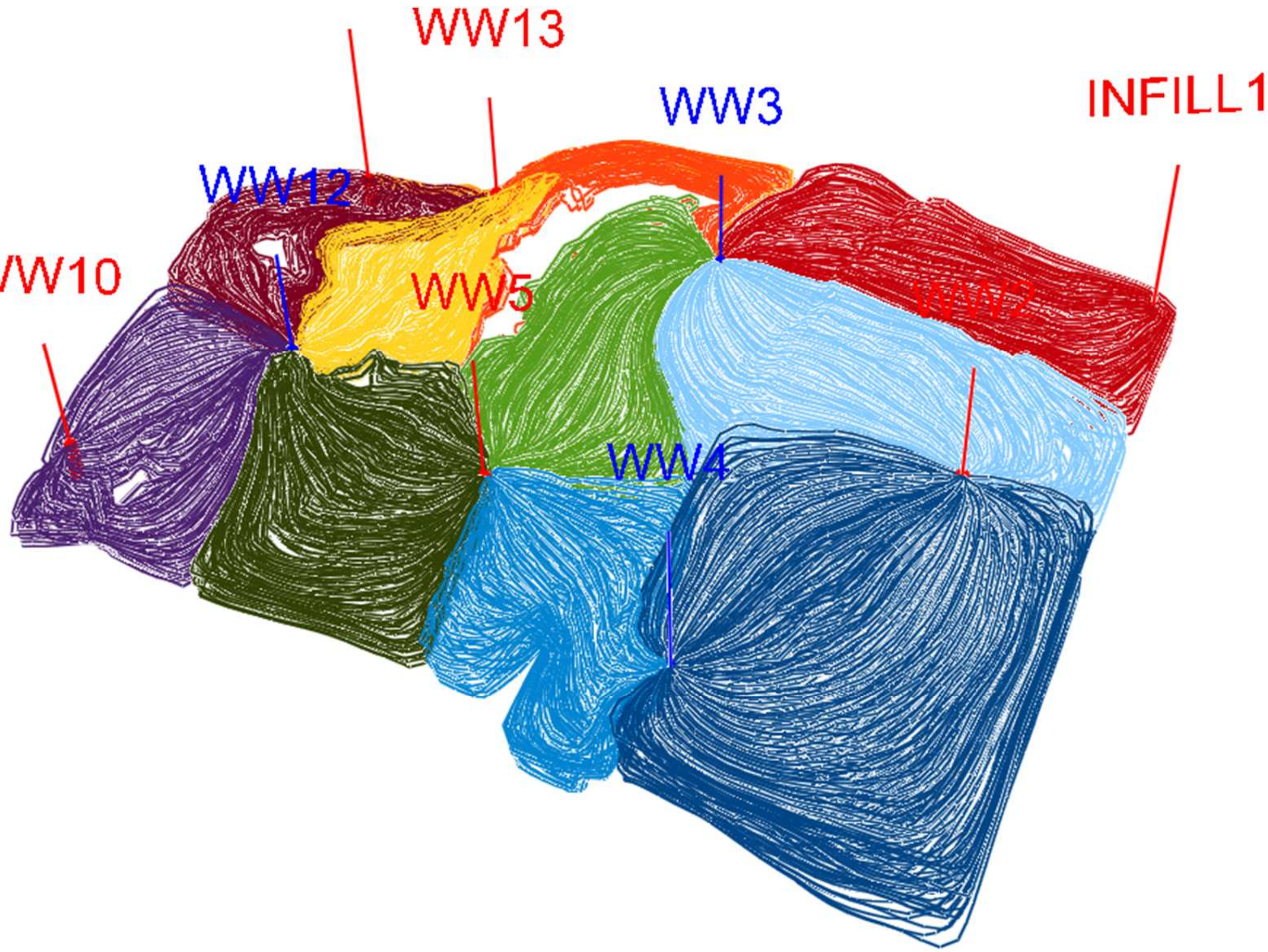
SL's change in time because of new wells and mobility changes.

Streamlines at t_4



SL's change in time because of new wells and mobility changes.

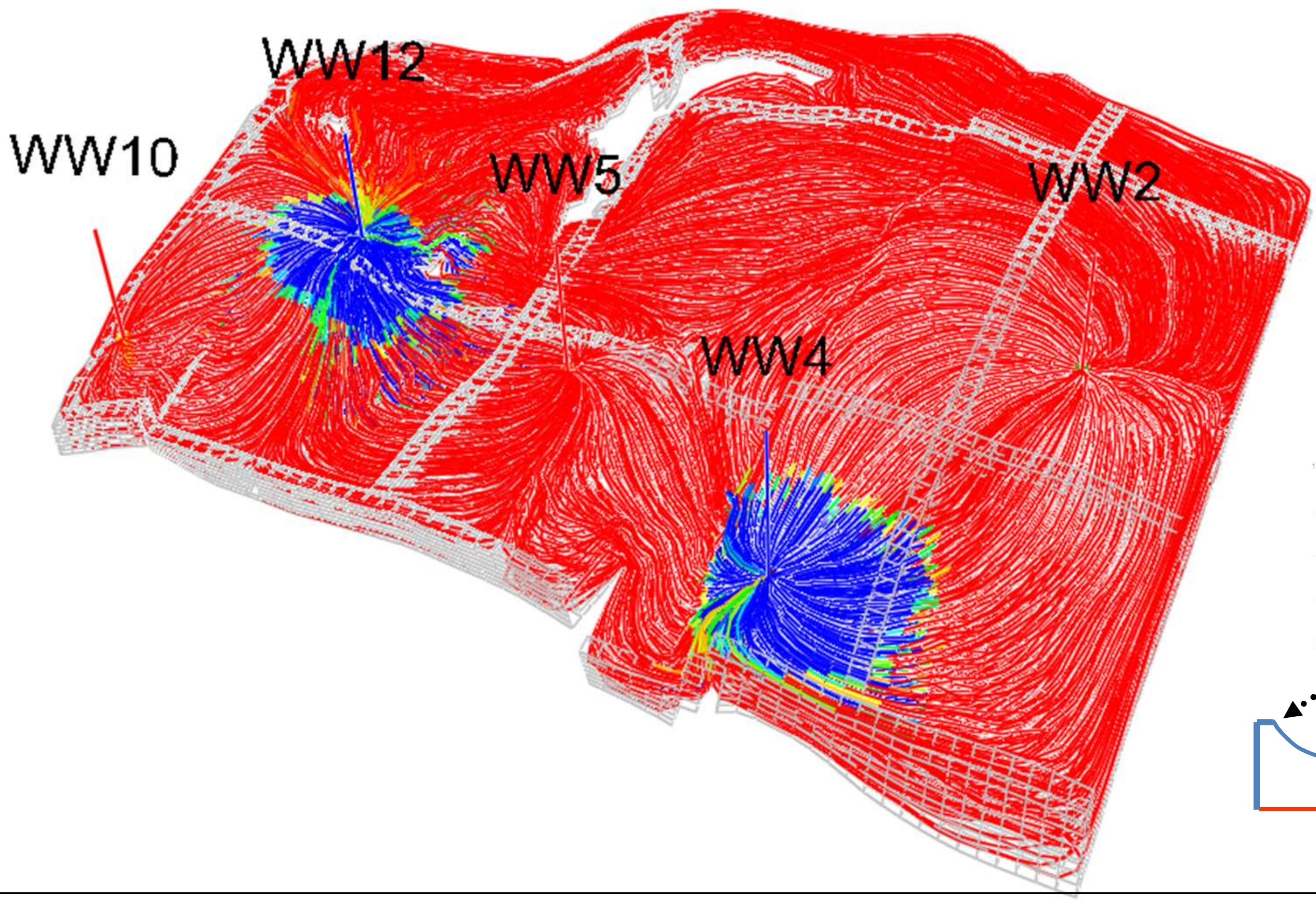
Streamlines at t_5

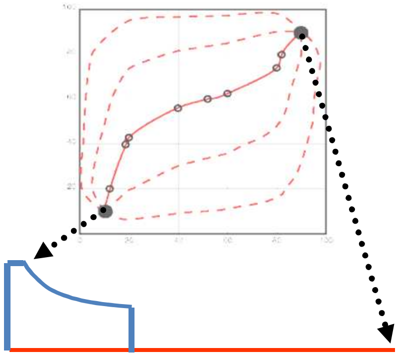


SL's change in time because of new wells and mobility changes.

MOVE SATURATIONS ALONG STREAMLINES

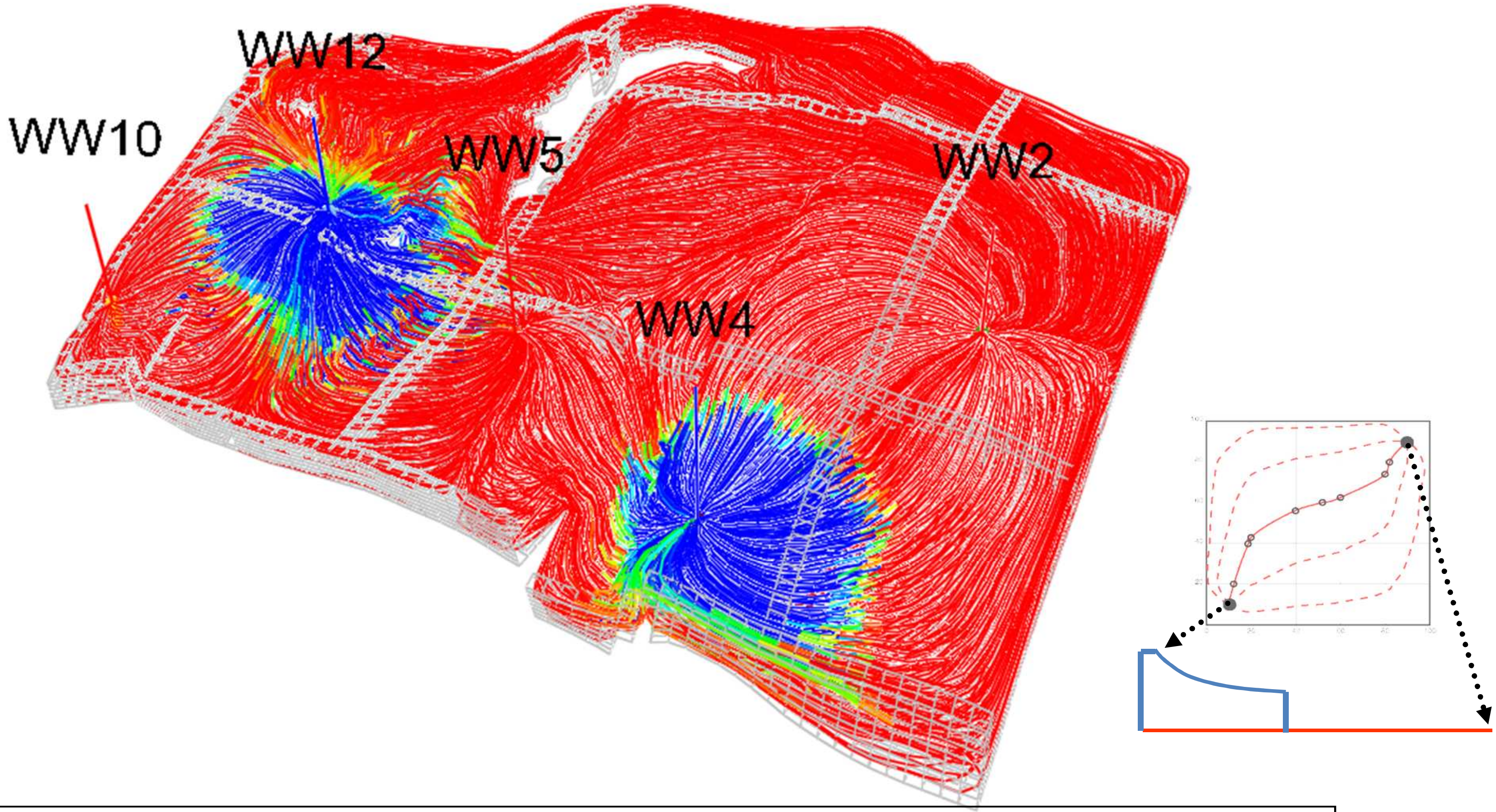
Transport Along Streamlines





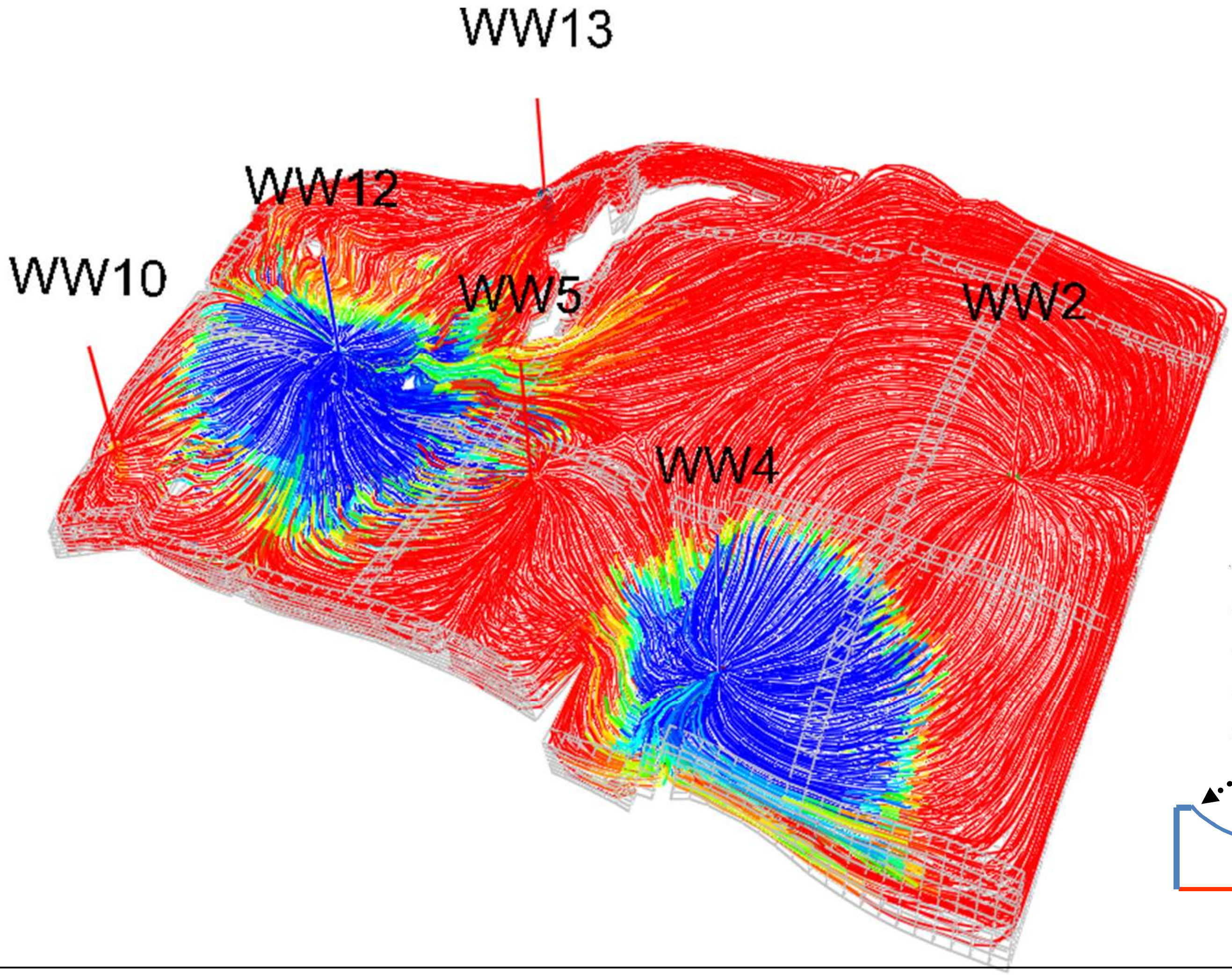
Transport components along 1D SL's numerically.

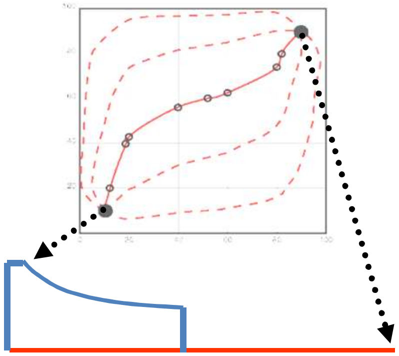
Transport Along Streamlines



Transport components along 1D SL's numerically.

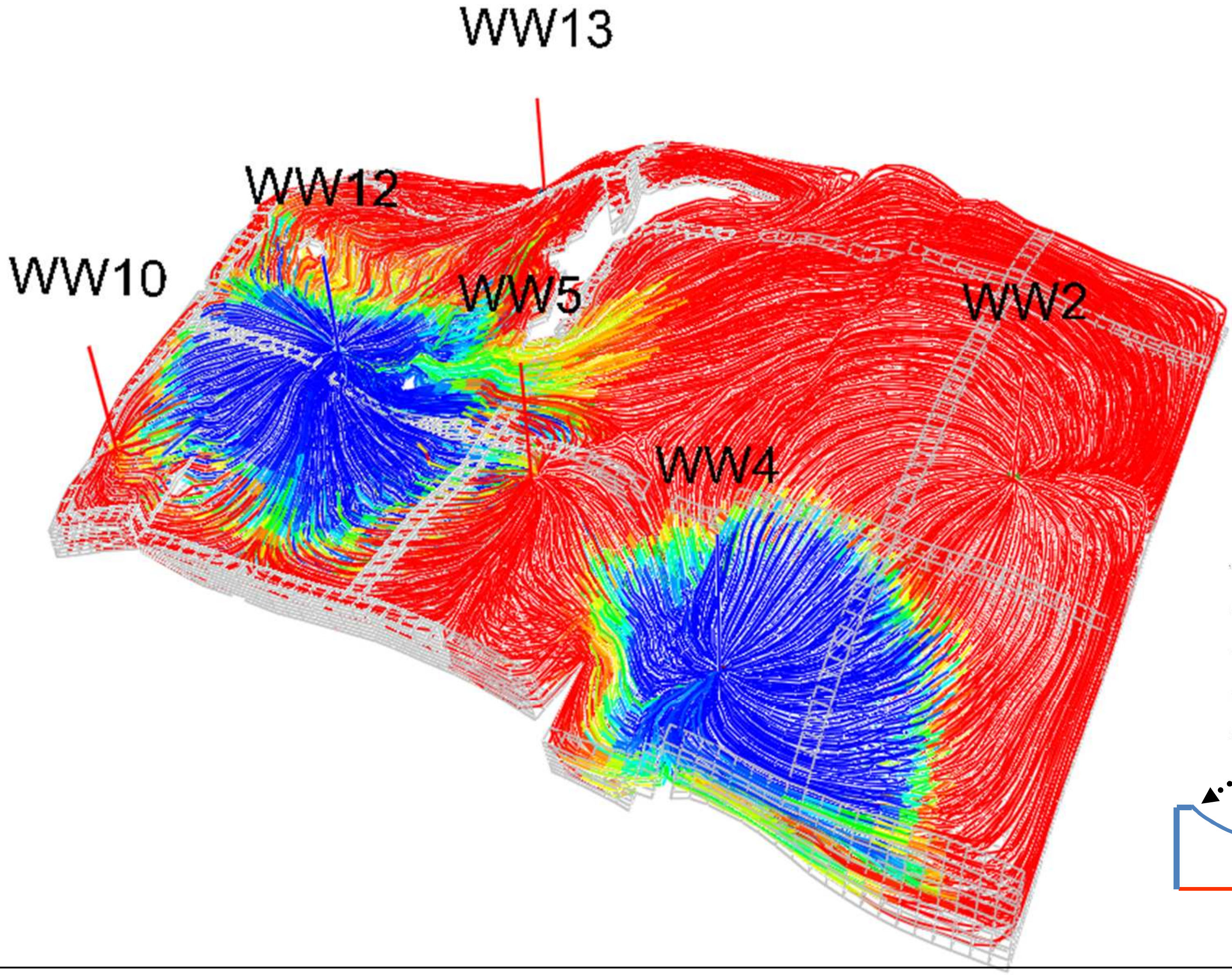
Transport Along Streamlines

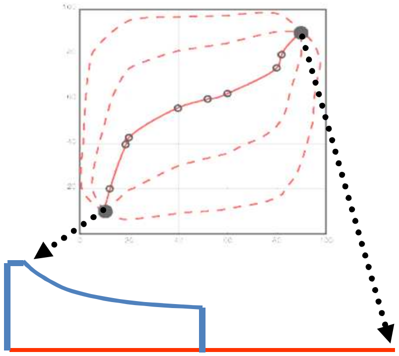




Transport components along 1D SL's numerically.

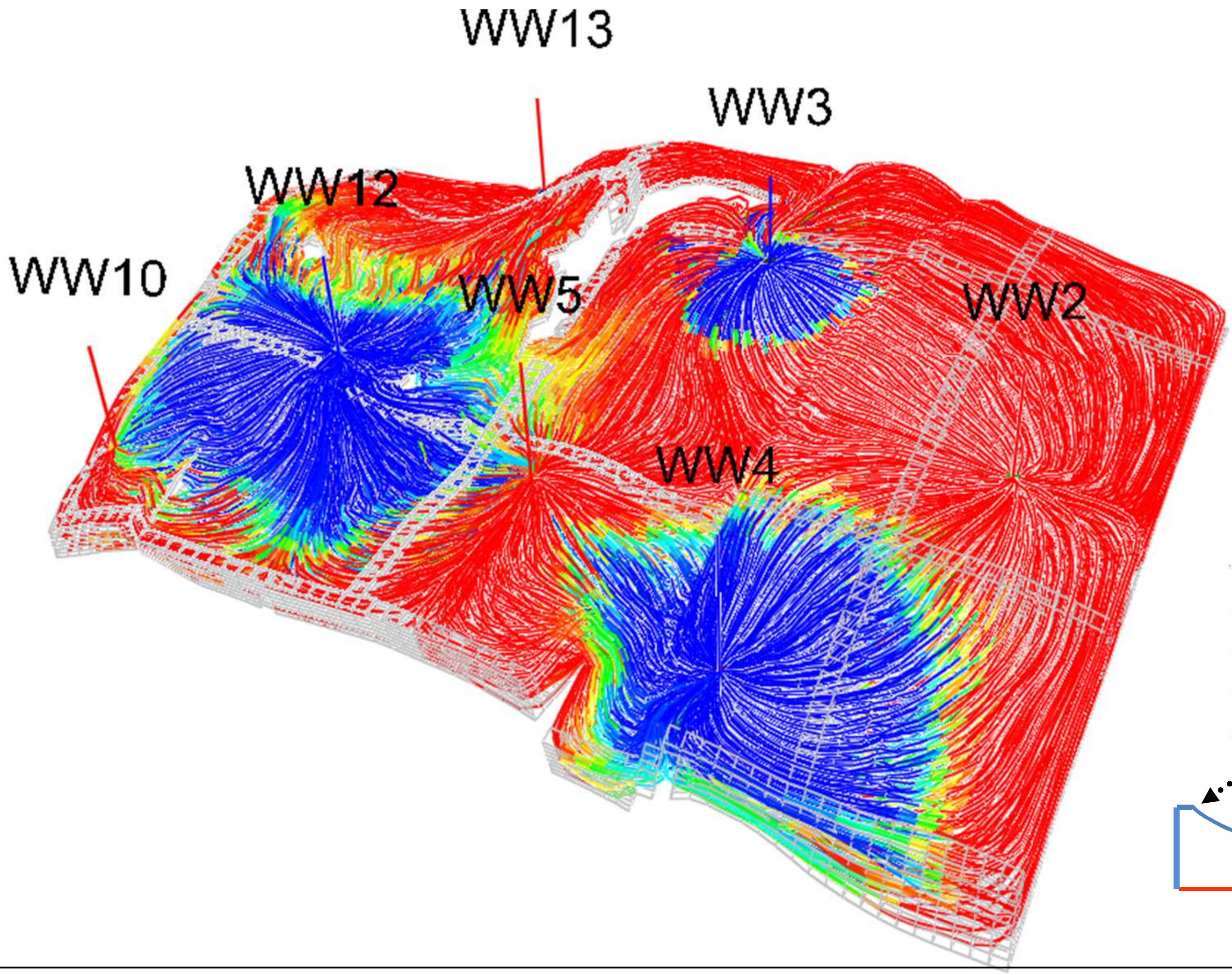
Transport Along Streamlines

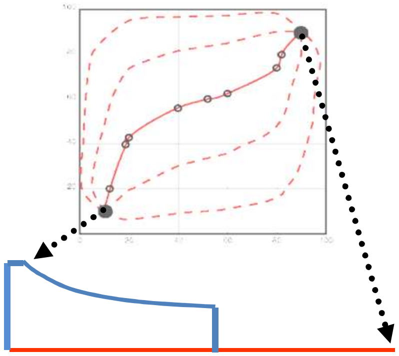




Transport components along 1D SL's numerically.

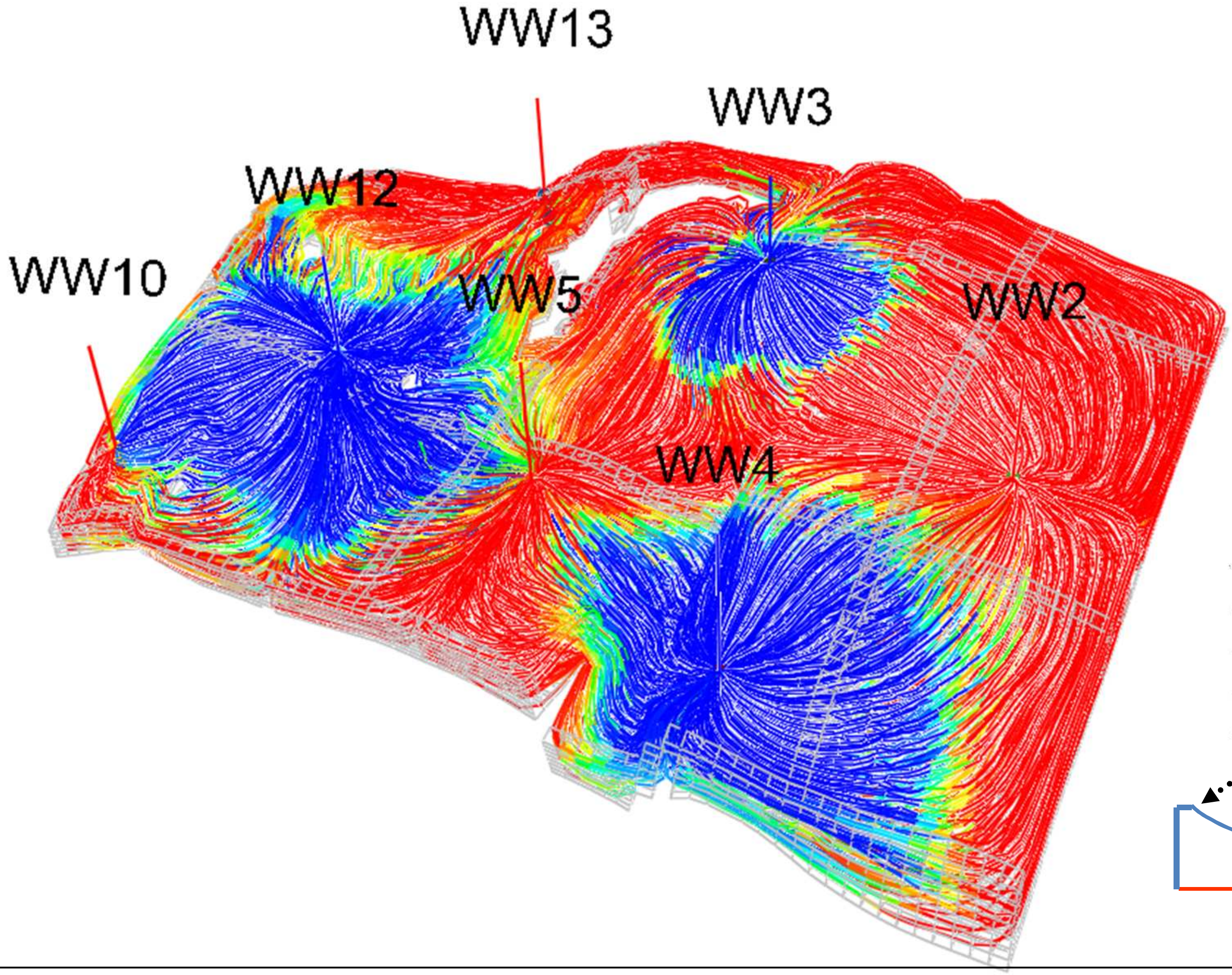
Transport Along Streamlines

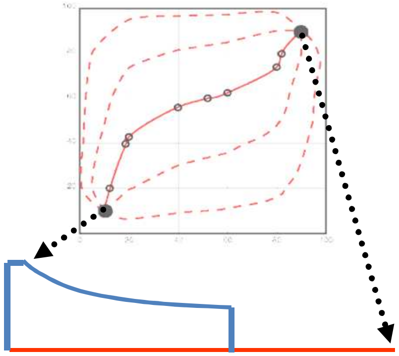




Transport components along 1D SL's numerically.

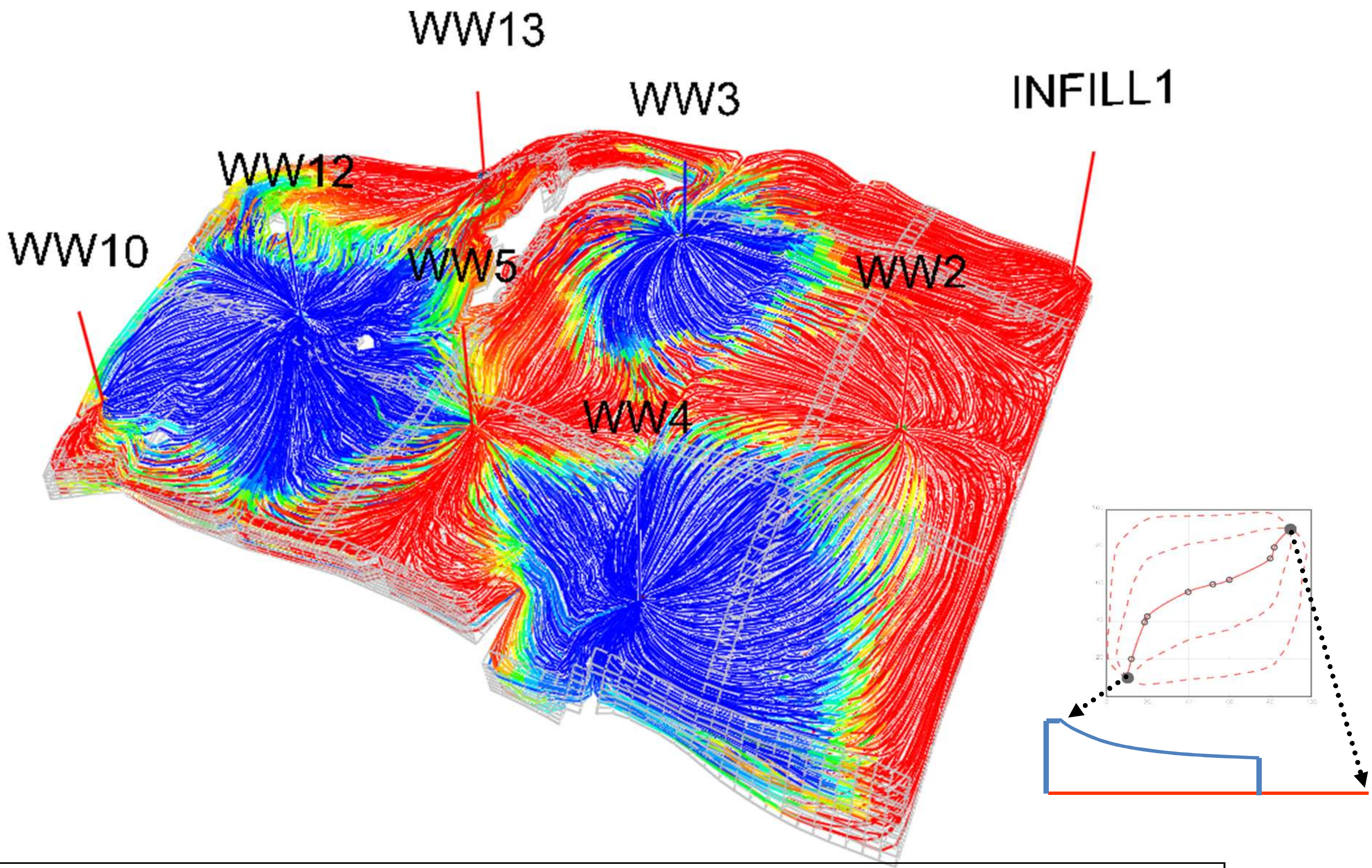
Transport Along Streamlines





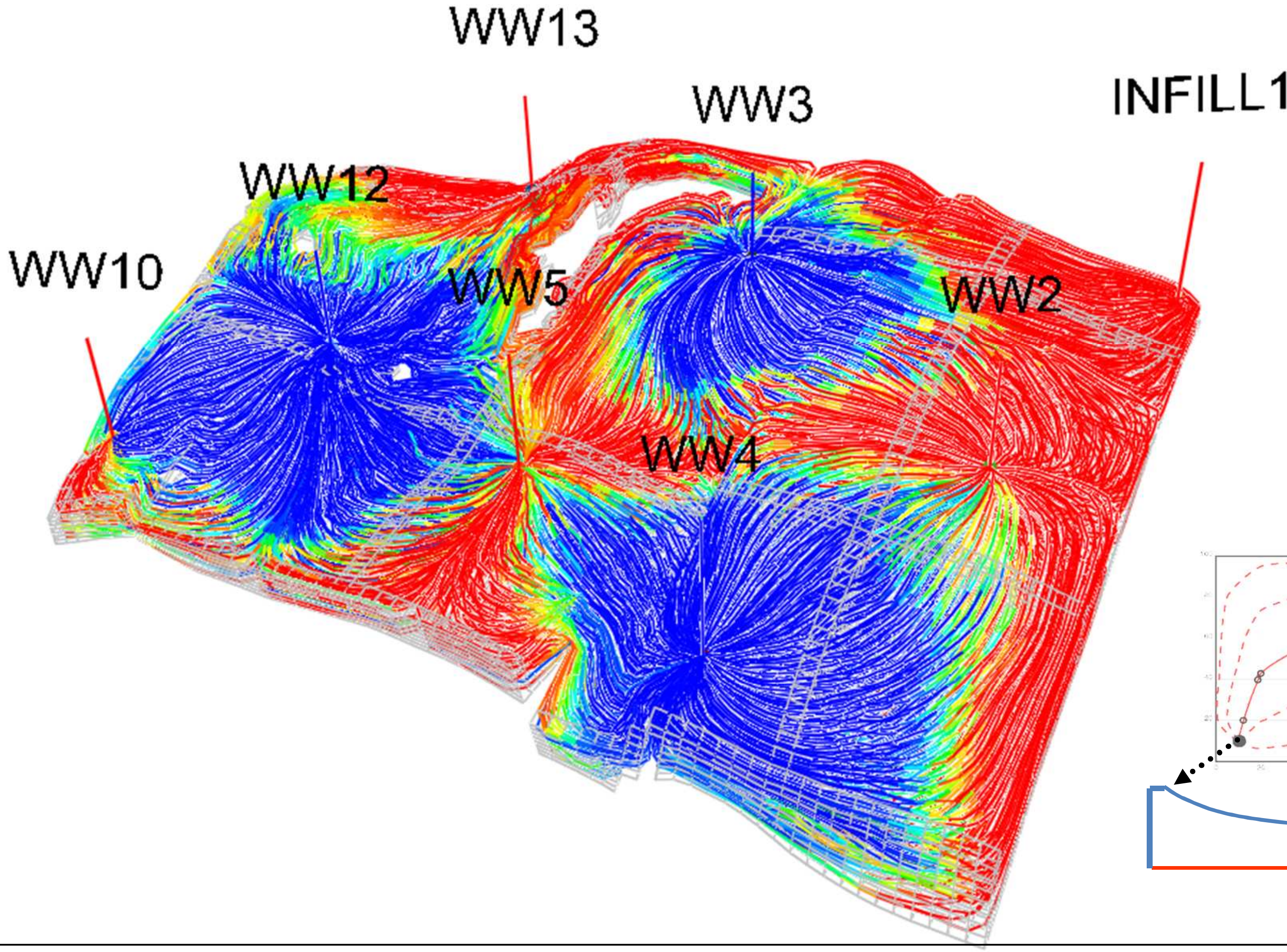
Transport components along 1D SL's numerically.

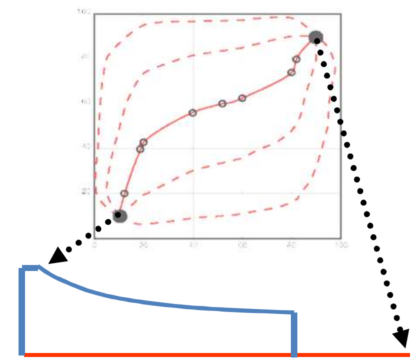
Transport Along Streamlines



Transport components along 1D SL's numerically.

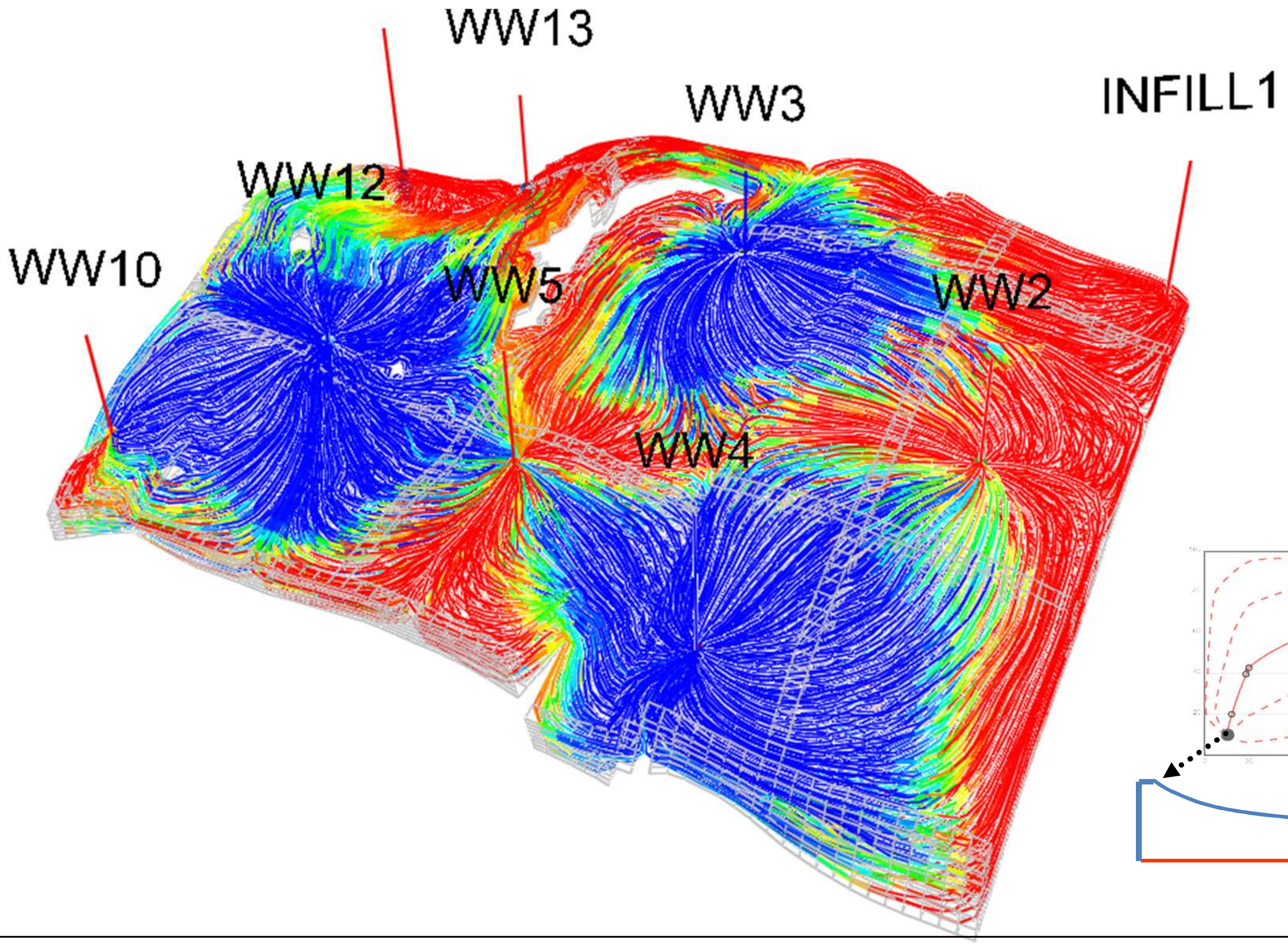
Transport Along Streamlines

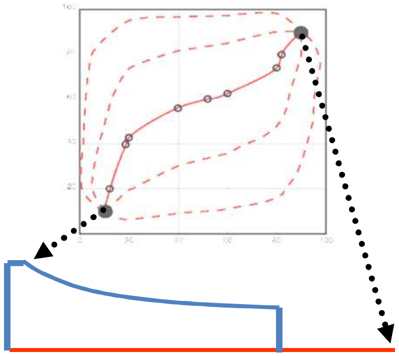




Transport components along 1D SL's numerically.

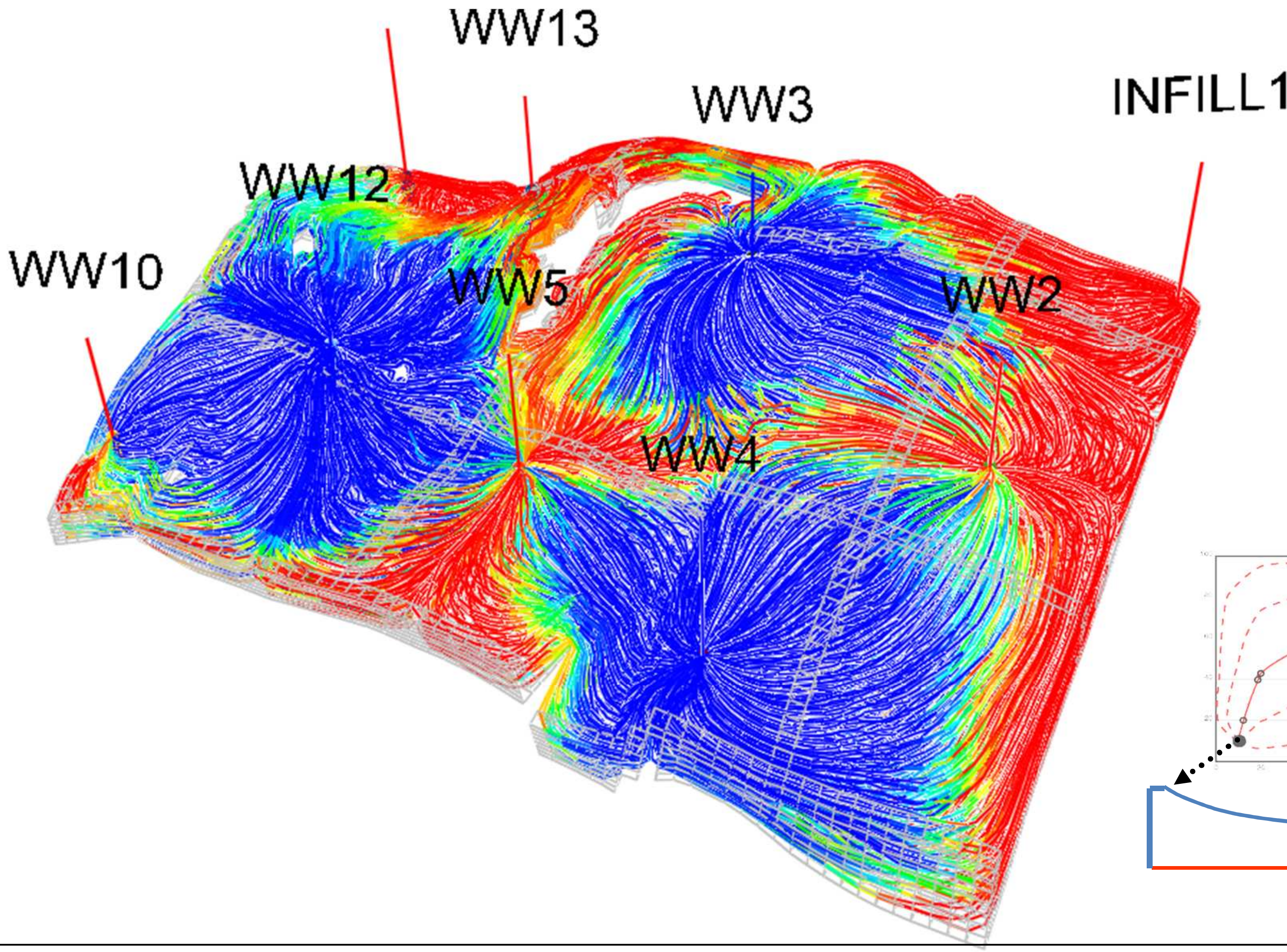
Transport Along Streamlines

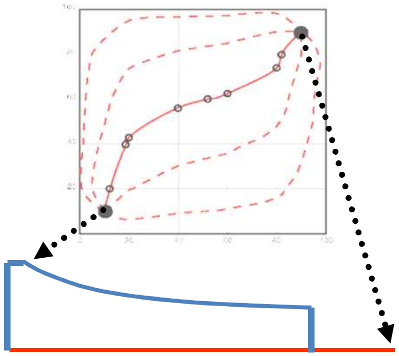




Transport components along 1D SL's numerically.

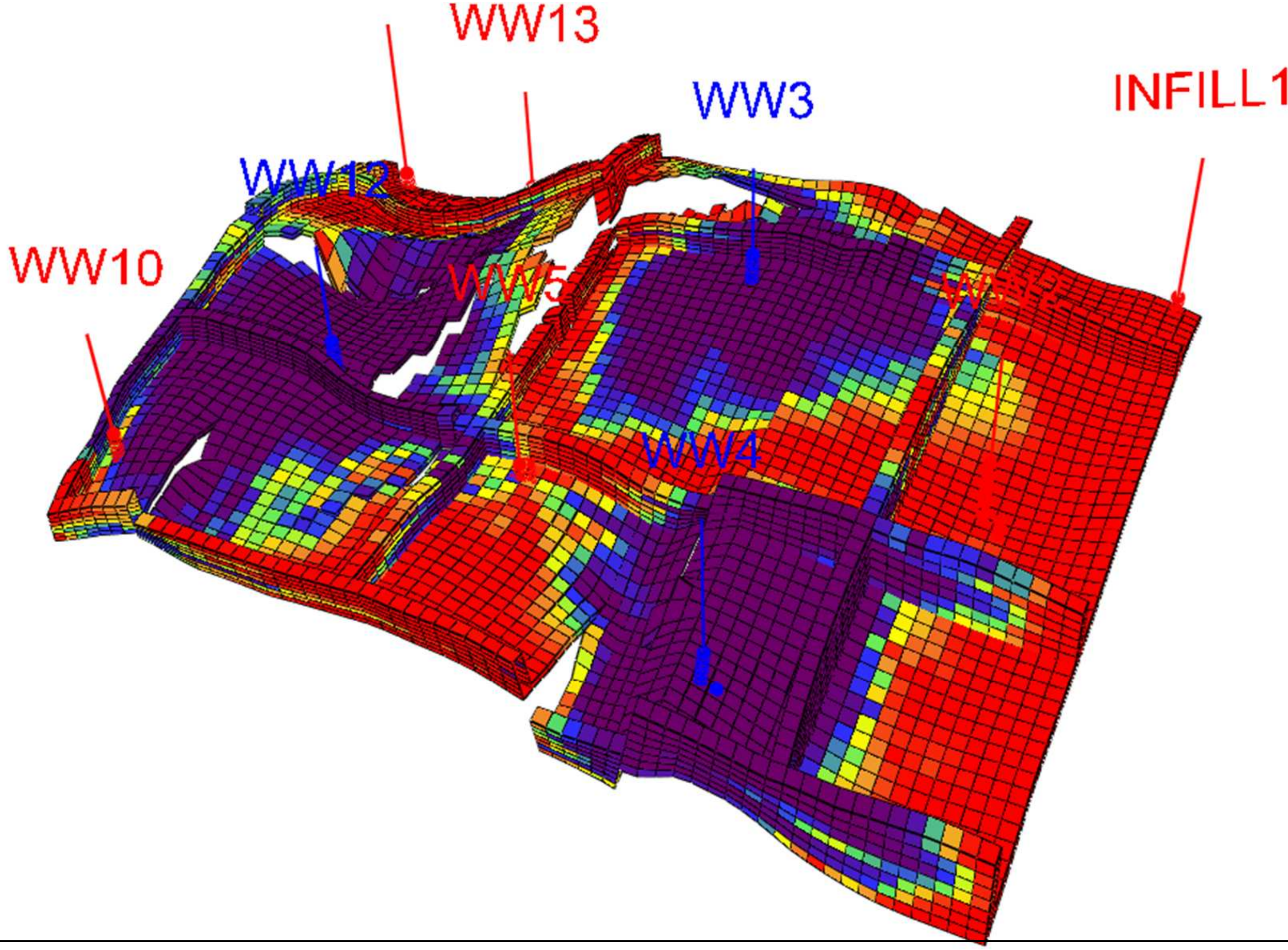
Transport Along Streamlines





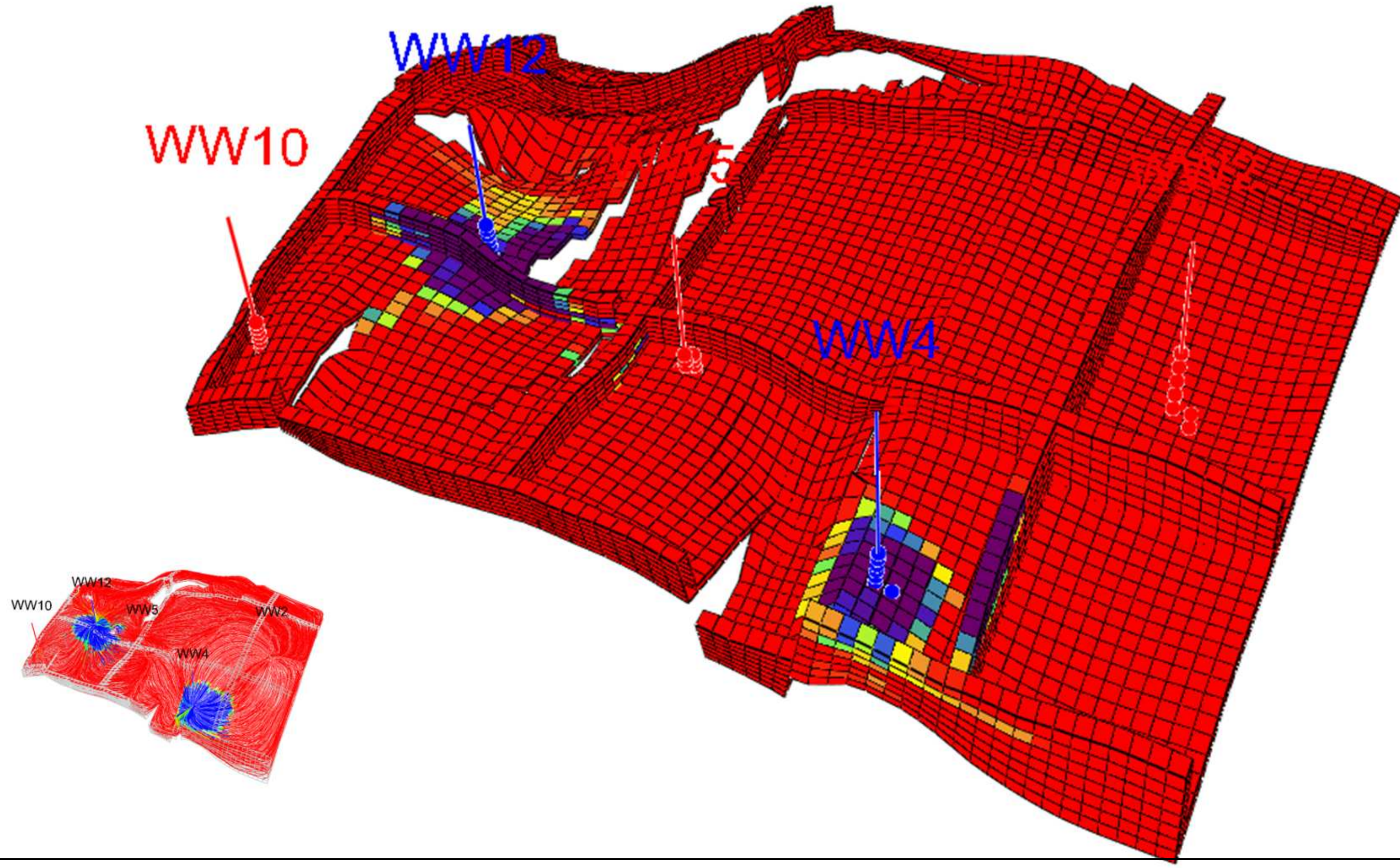
Transport components along 1D SL's numerically.

Mapping to/from SLs



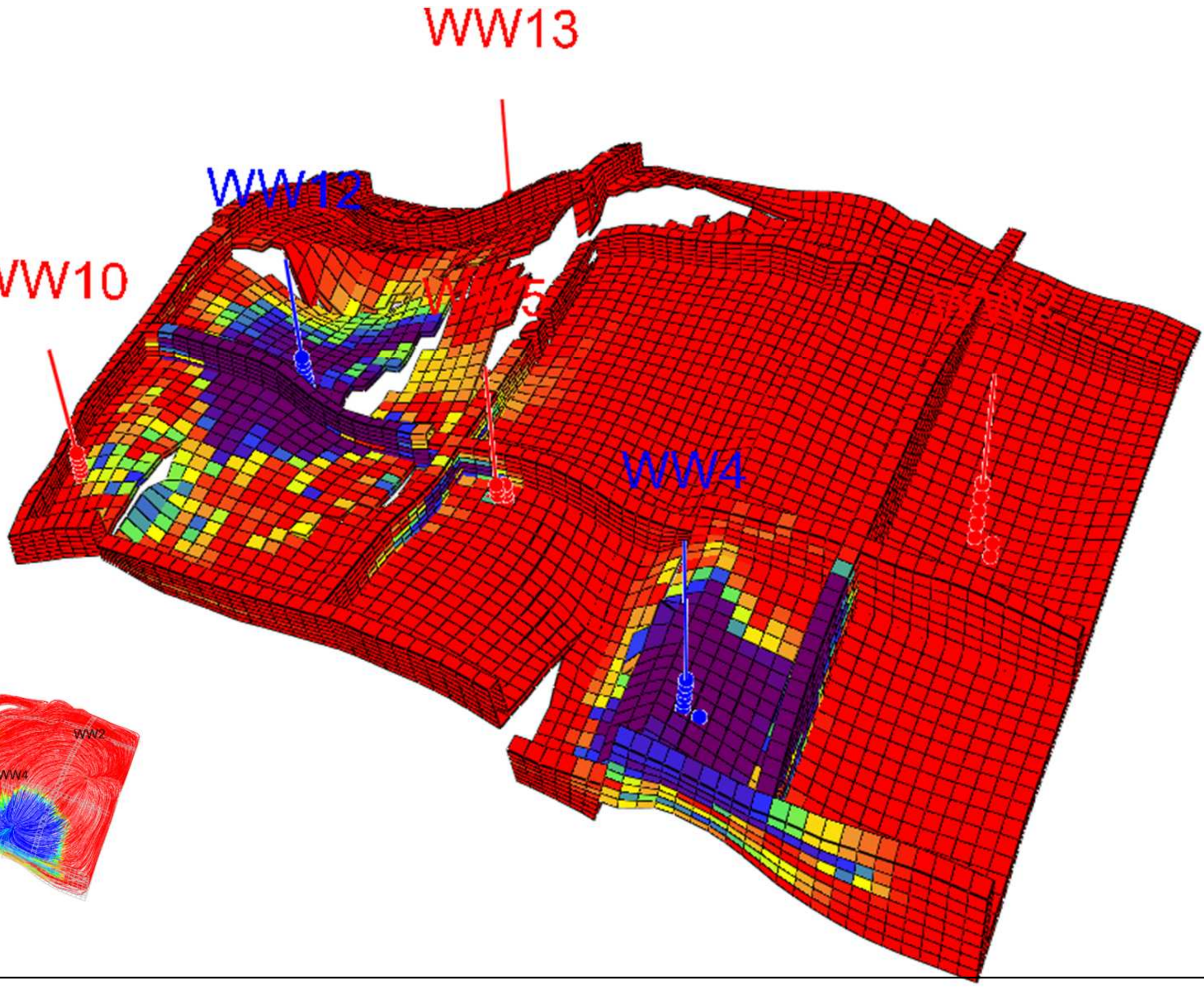
You can always map from SL's to static grid and vice versa.

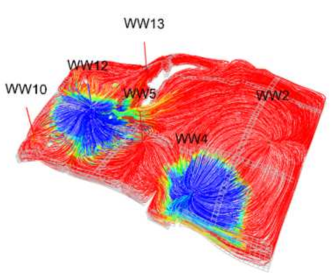
Saturations at Time 1



You can always map from SL's to static grid and vice versa.

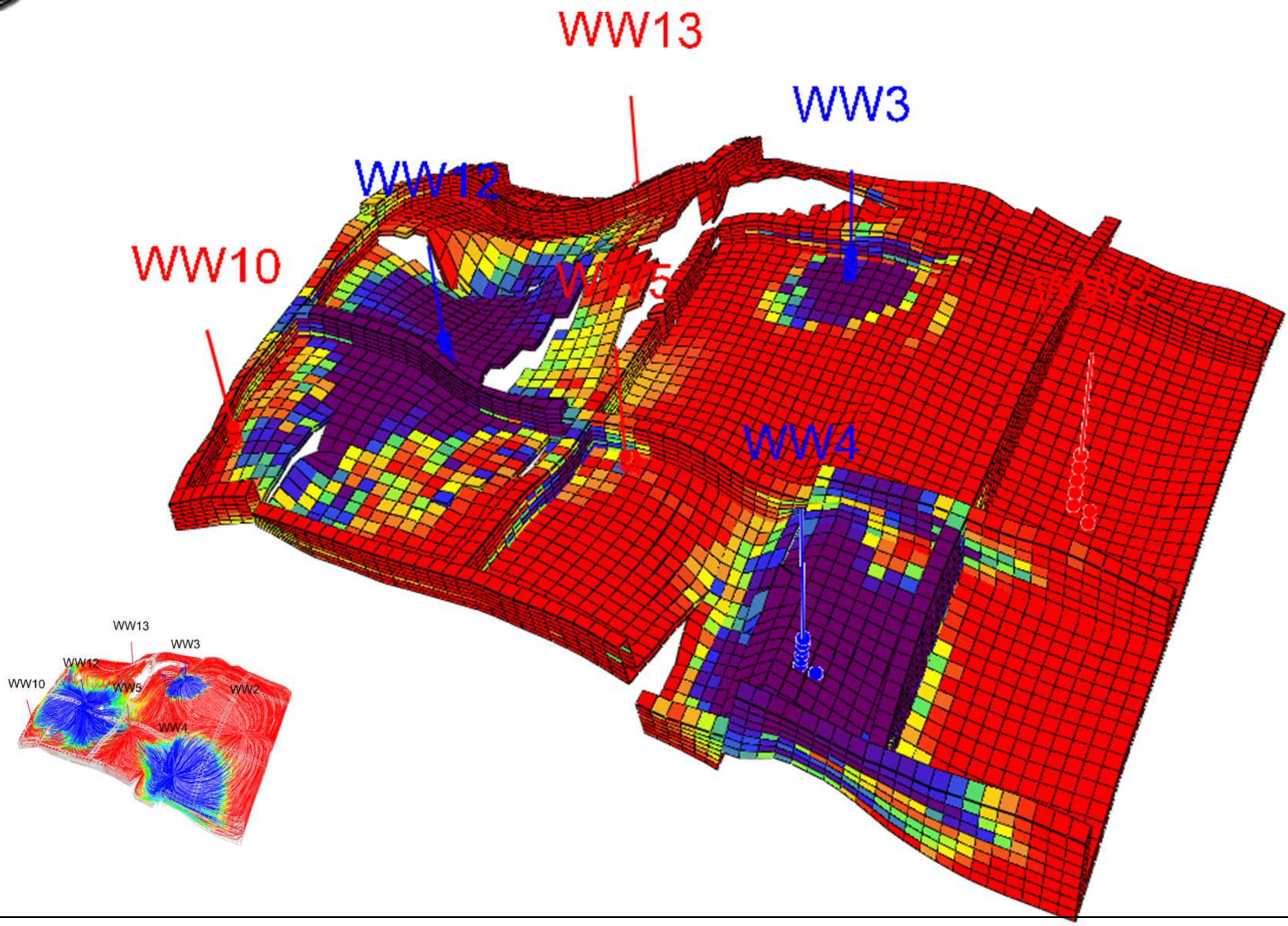
Saturations at Time 2





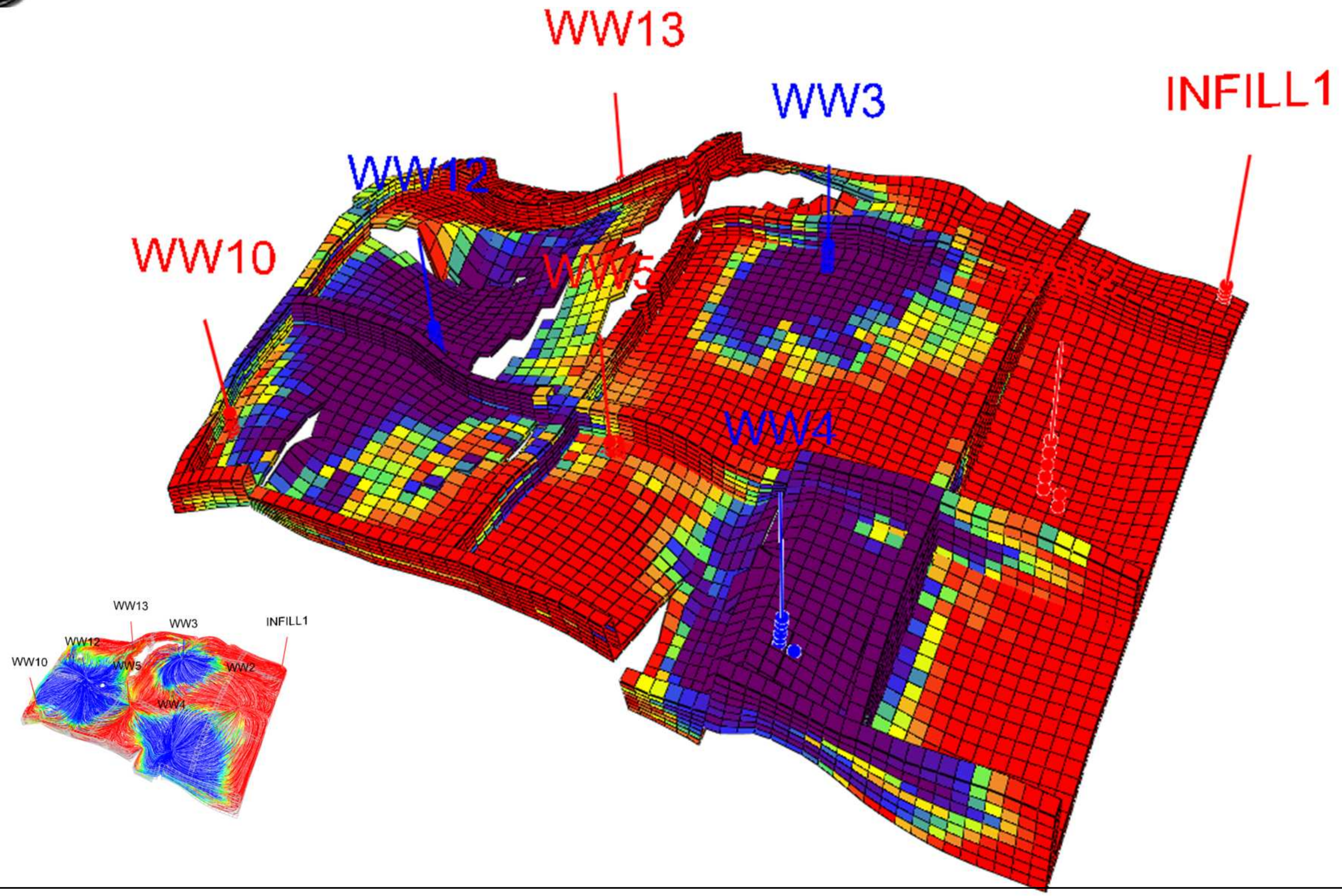
You can always map from SL's to static grid and vice versa.

Saturations at Time 3



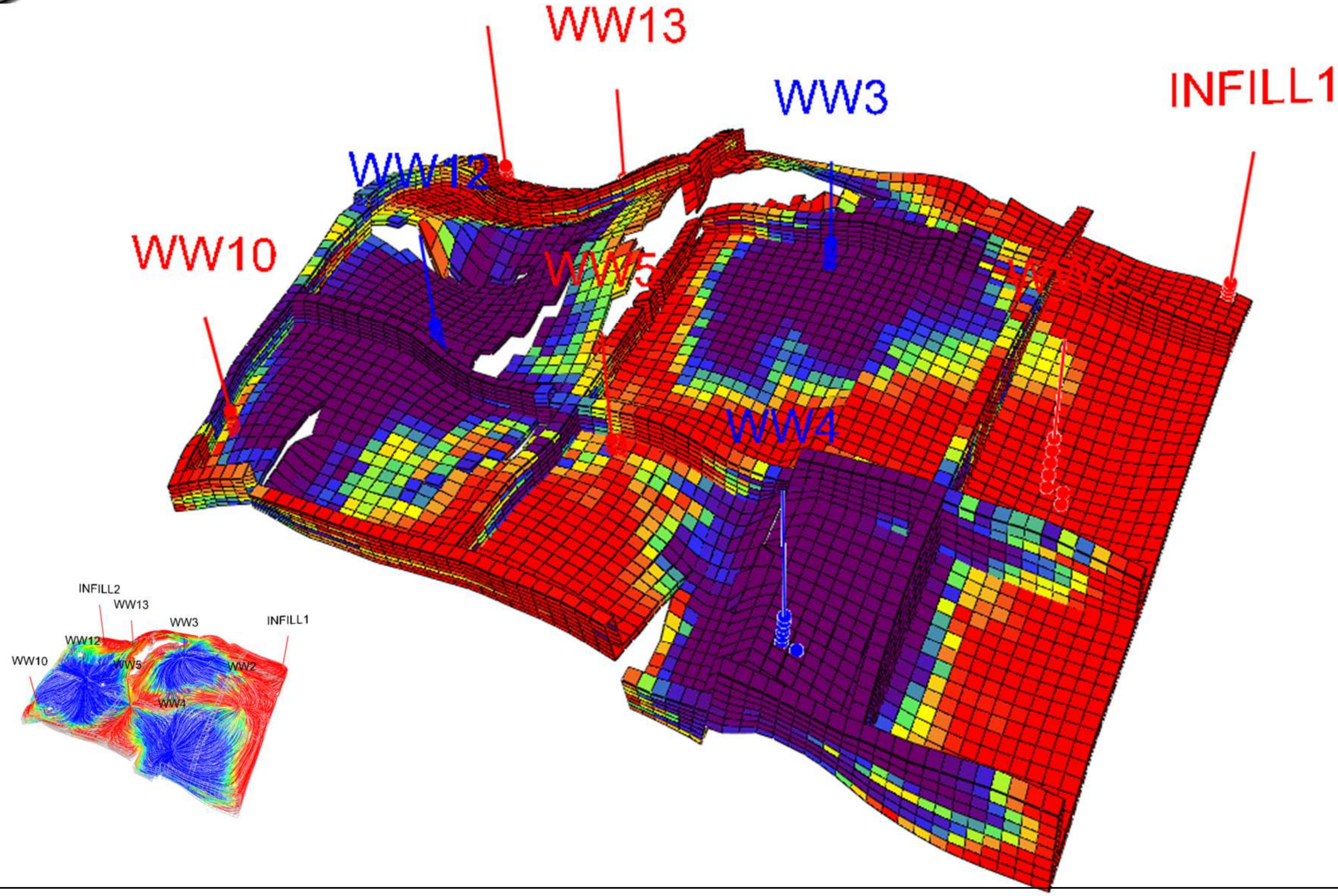
You can always map from SL's to static grid and vice versa.

Saturations at Time 4

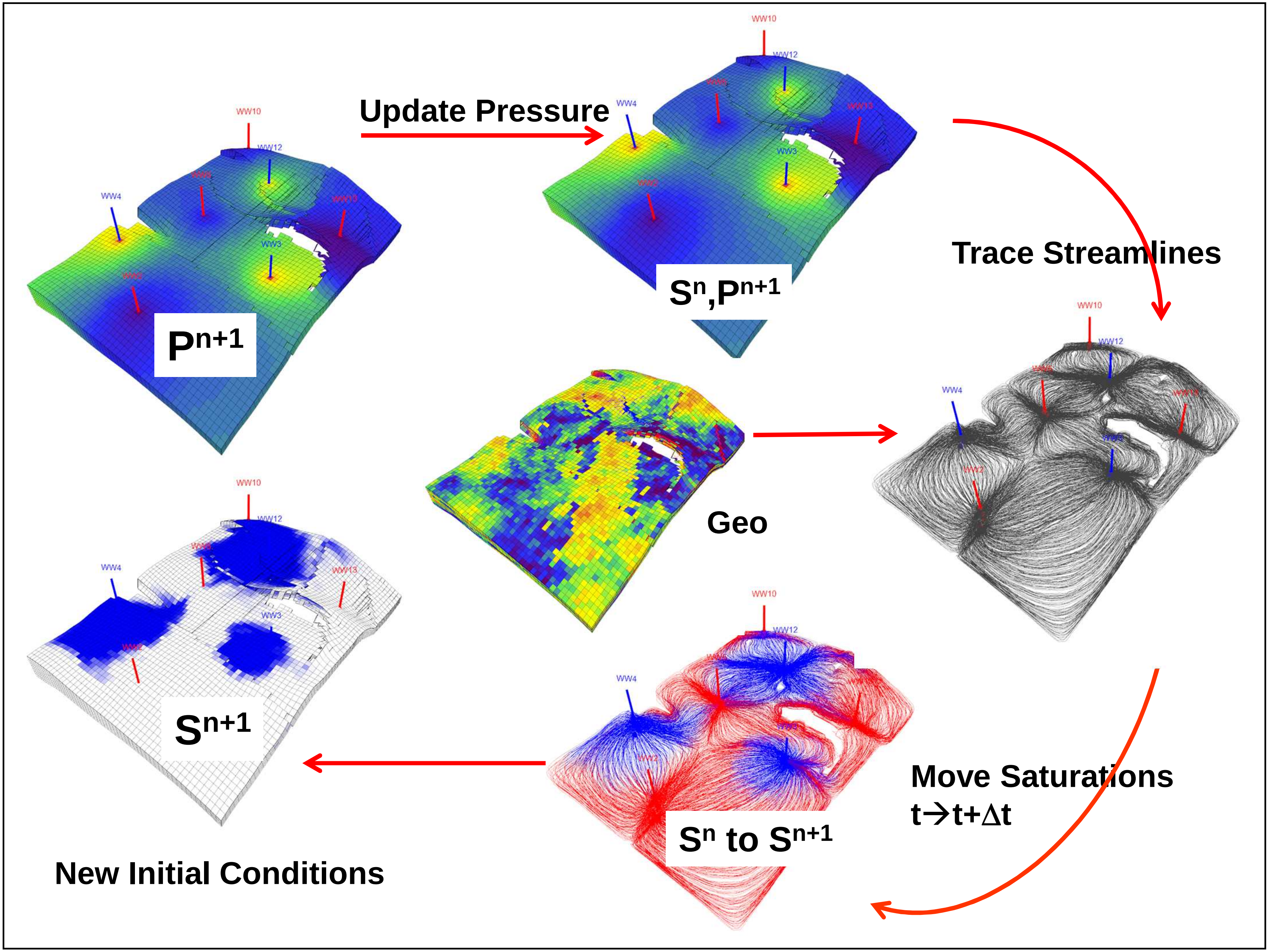


You can always map from SL's to static grid and vice versa.

Saturations at Time 5



You can always map from SL's to static grid and vice versa.



Update Pressure
S^n, P^{n+1}
P^{n+1}
Trace Streamlines
Geo
Move Saturations
$t \rightarrow t+\Delta t$
S^n to S^{n+1}
S^{n+1}
New Initial Conditions

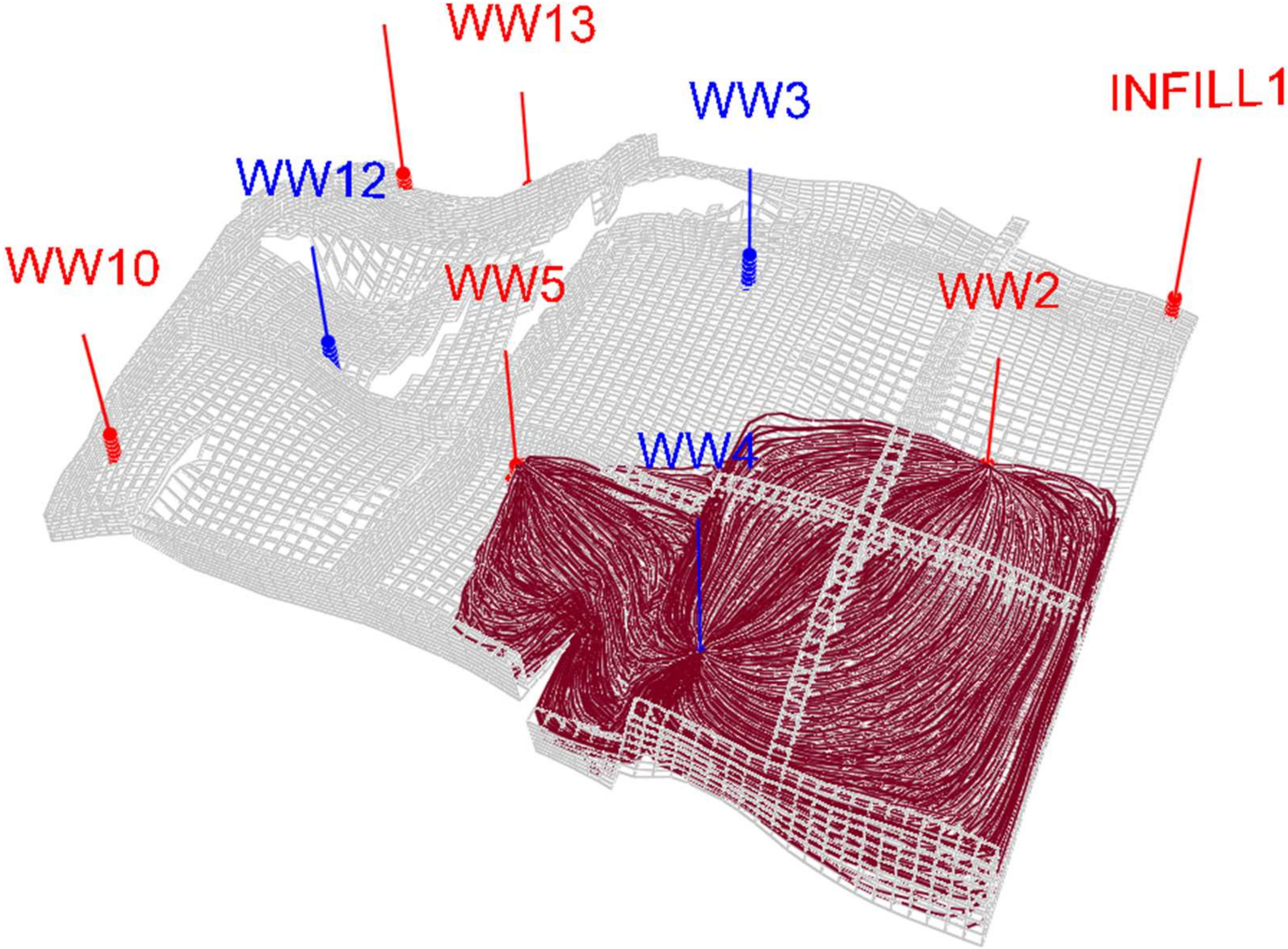
SLs New Data

Streamlines' new data sources:

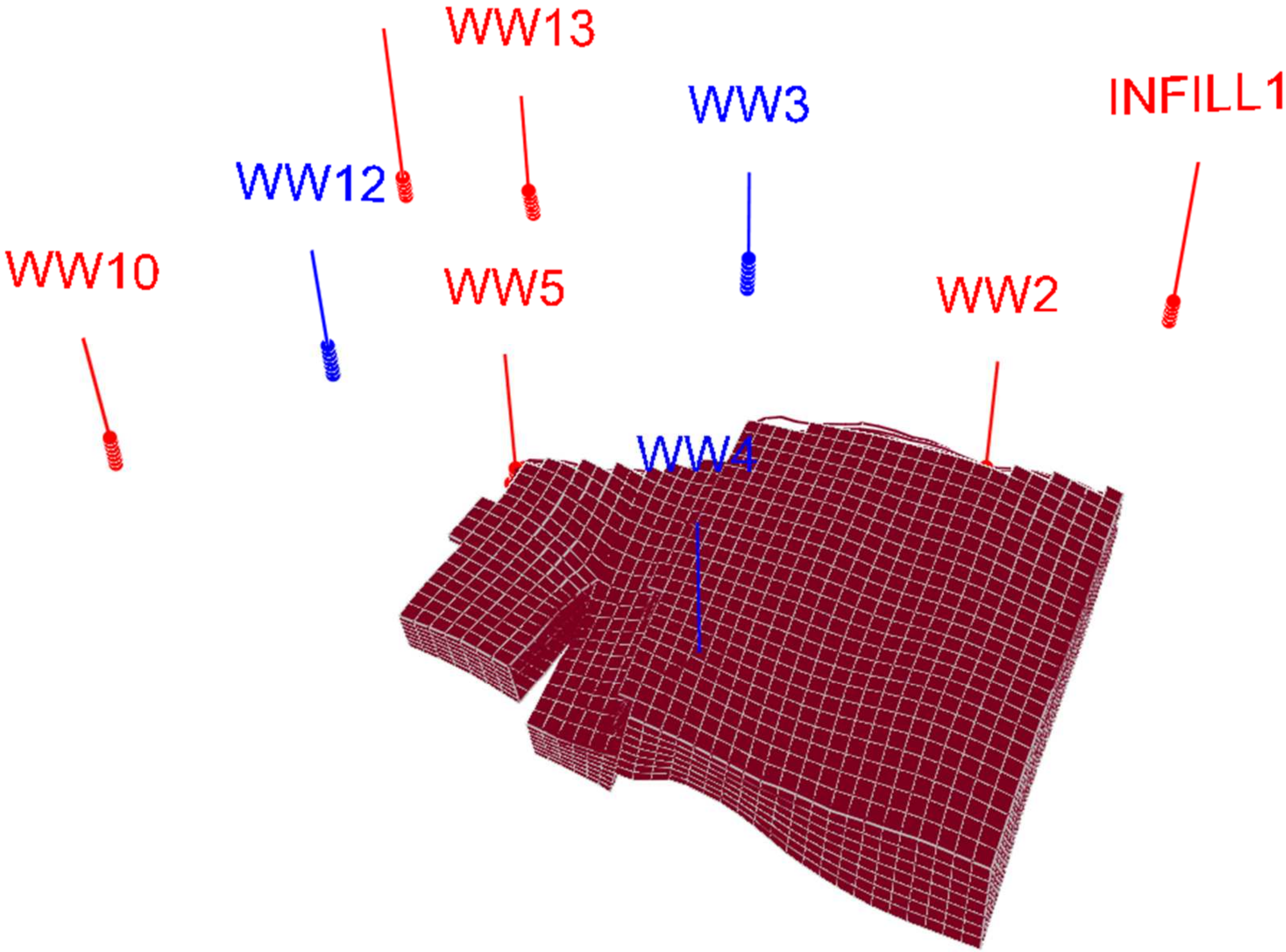
- The streamlines themselves.
  - Visually appealing and intuitive.
- Drainage/irrigation well pore volumes.
  - Estimate of dynamic reservoir volumes of individual wells.
- The dynamic flux pattern maps.
  - A compact way to quantify connectivity and well patterns.

DRAINAGE/IRRIGATION VOLUMES

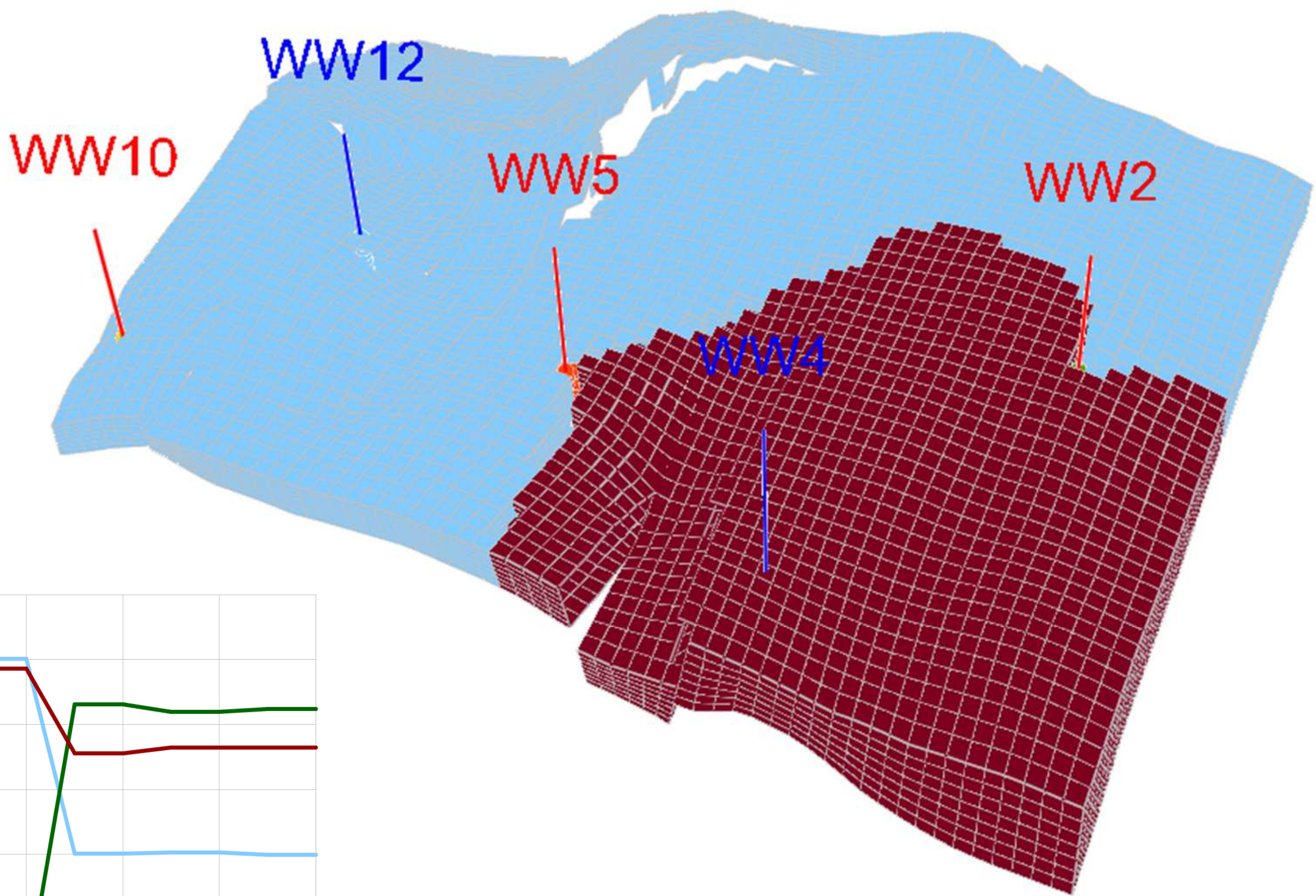
Well Pore Volumes



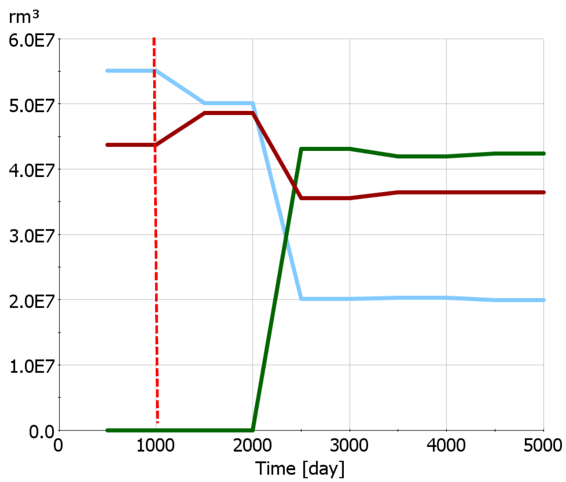
Irrigation Volumes (Injectors)



Time 1



WW12
WW10
WW5
WW2
WW4



rm³
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5.0E7
4.0E7
3.0E7
2.0E7
1.0E7
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2000
3000
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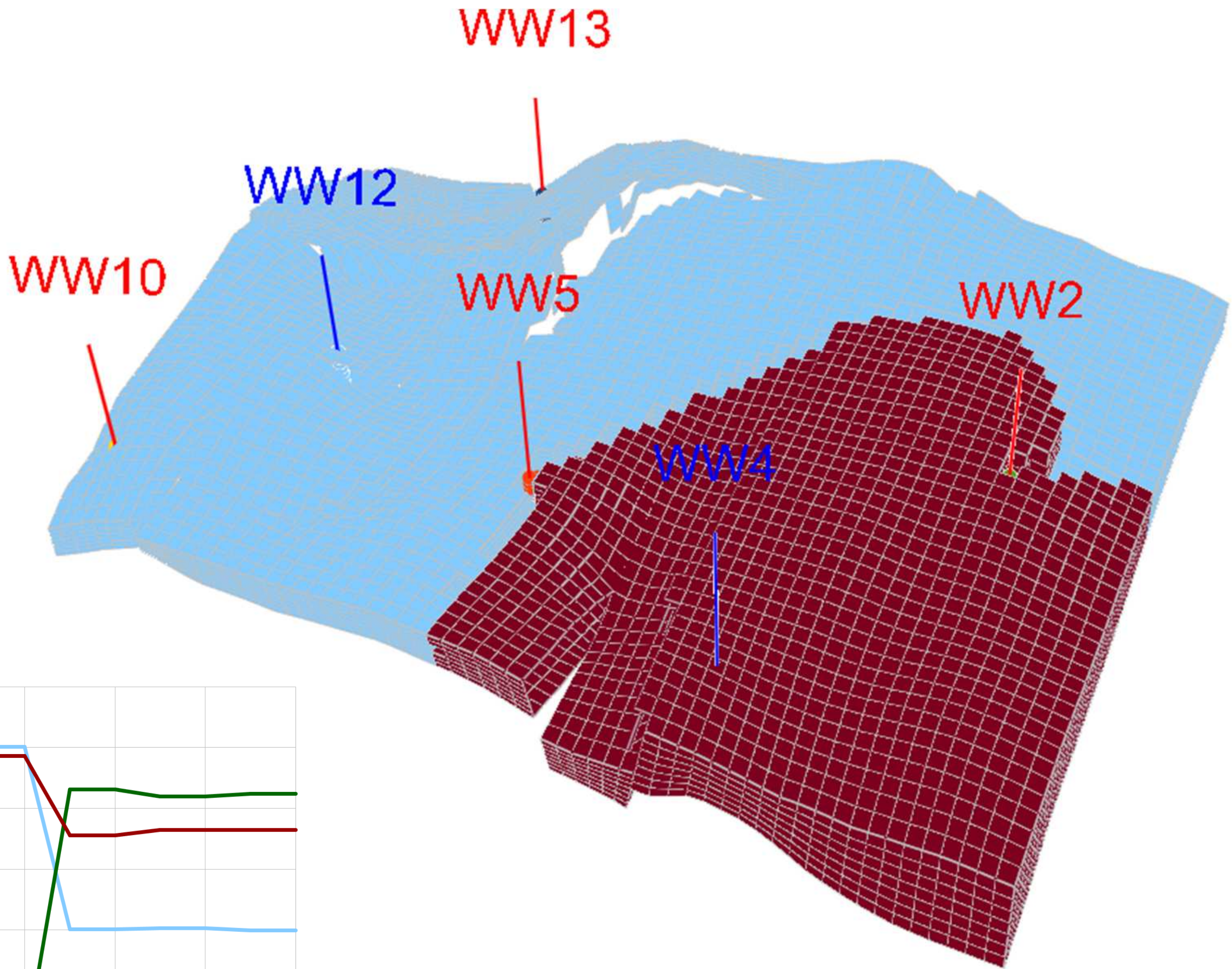
5000
Time [day]

Time 2



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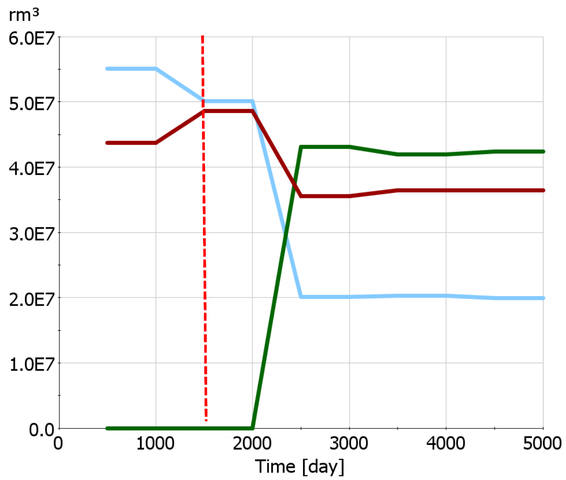
WW12
WW10
WW5
WW2
WW4



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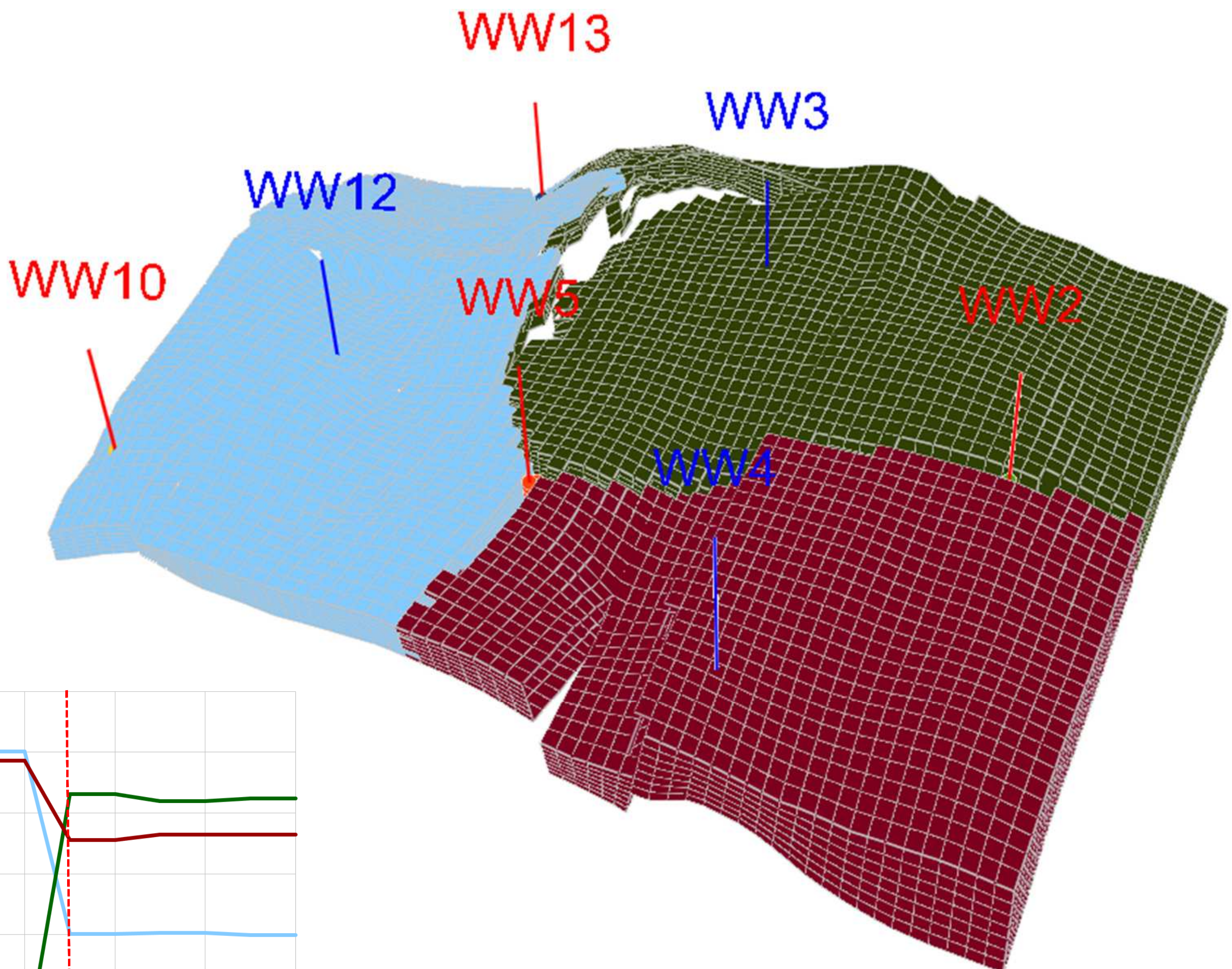
Time [day]

Time 3



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WW3
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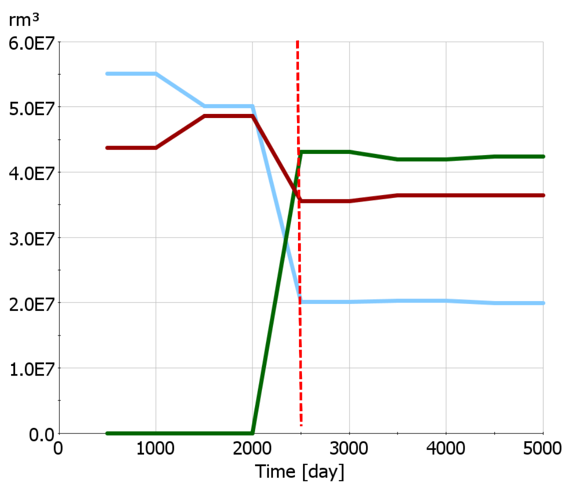
WW10
WW5
WW2
WW4



rm³
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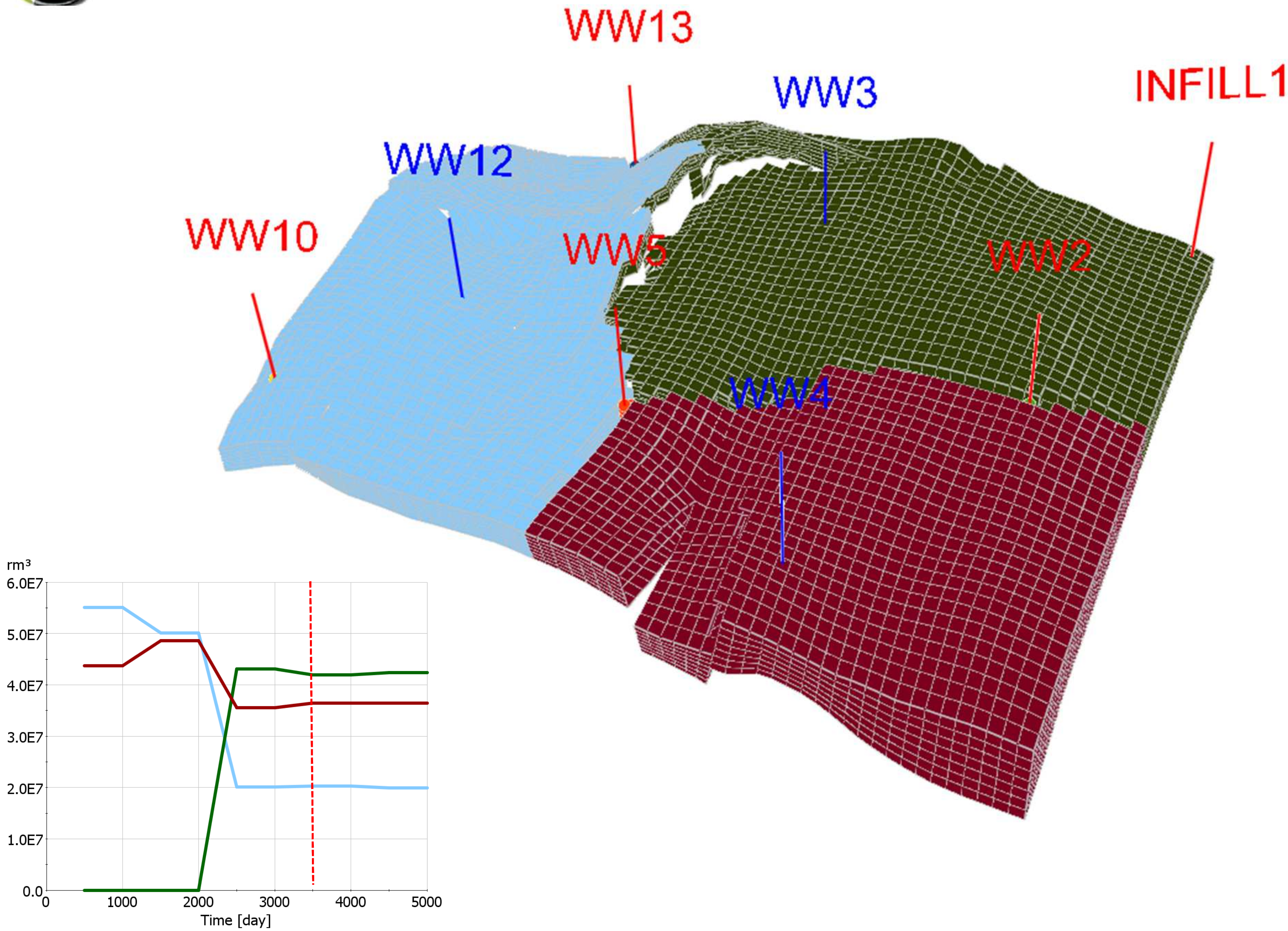
Time [day]

Time 4


WW13
WW3
INFILL1
WW12
WW10
WW5
WW2
WW4
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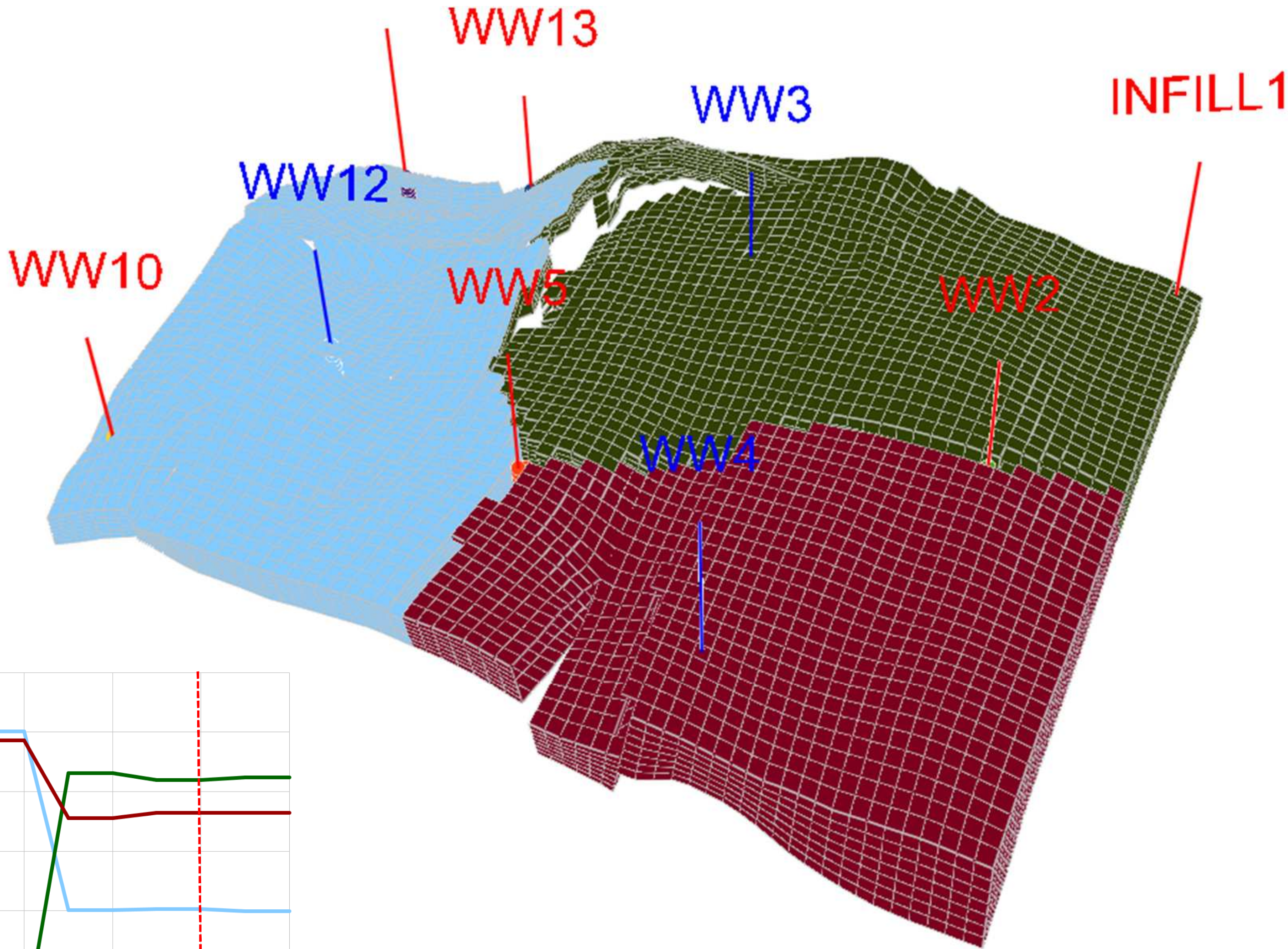
Time [day]

Time 5



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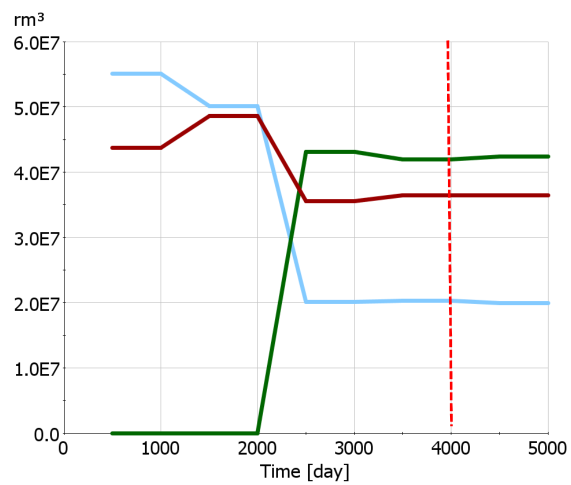
WW3
INFILL1
WW12
WW10
WW5
WW2
WW4



rm³
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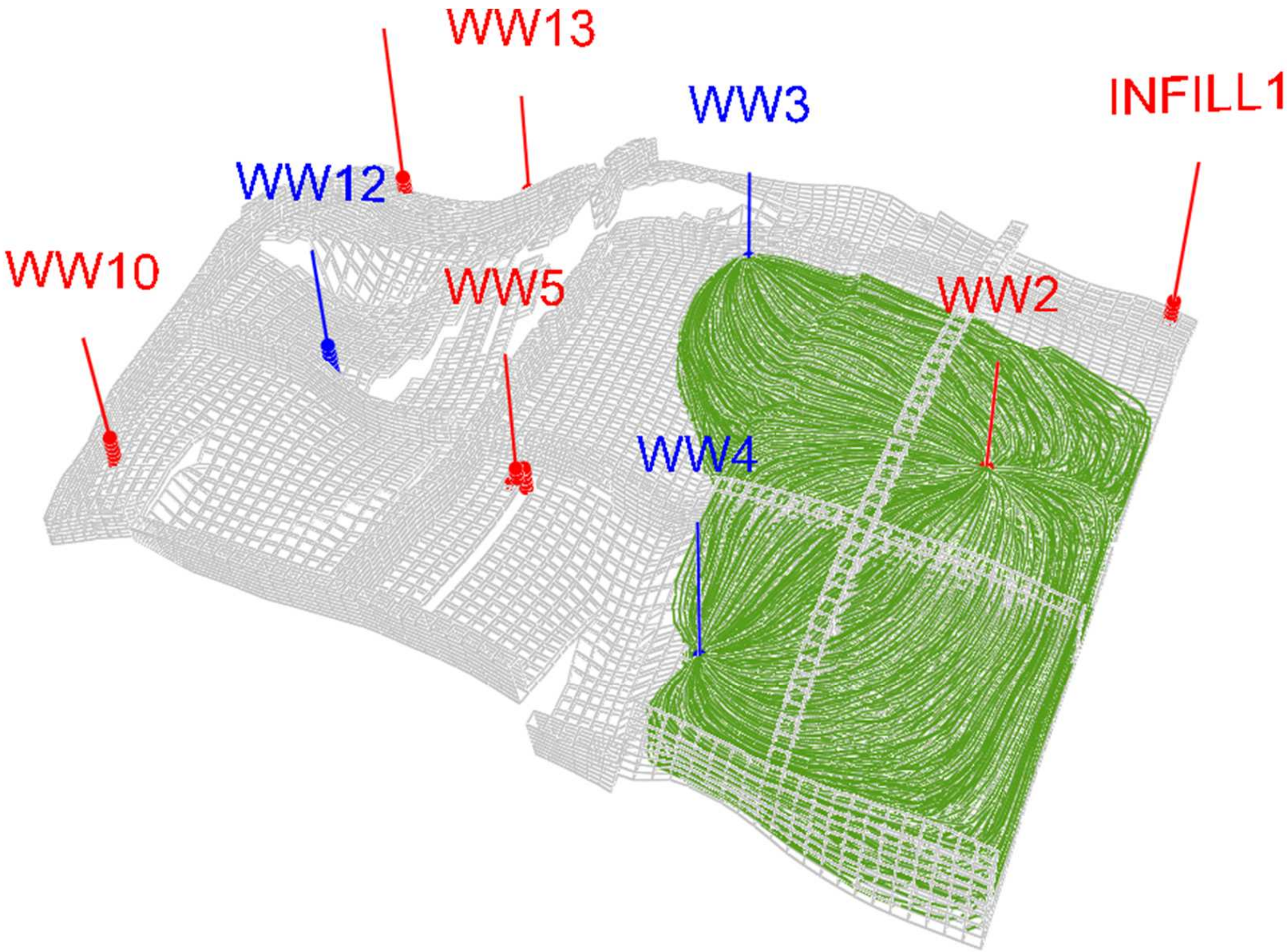
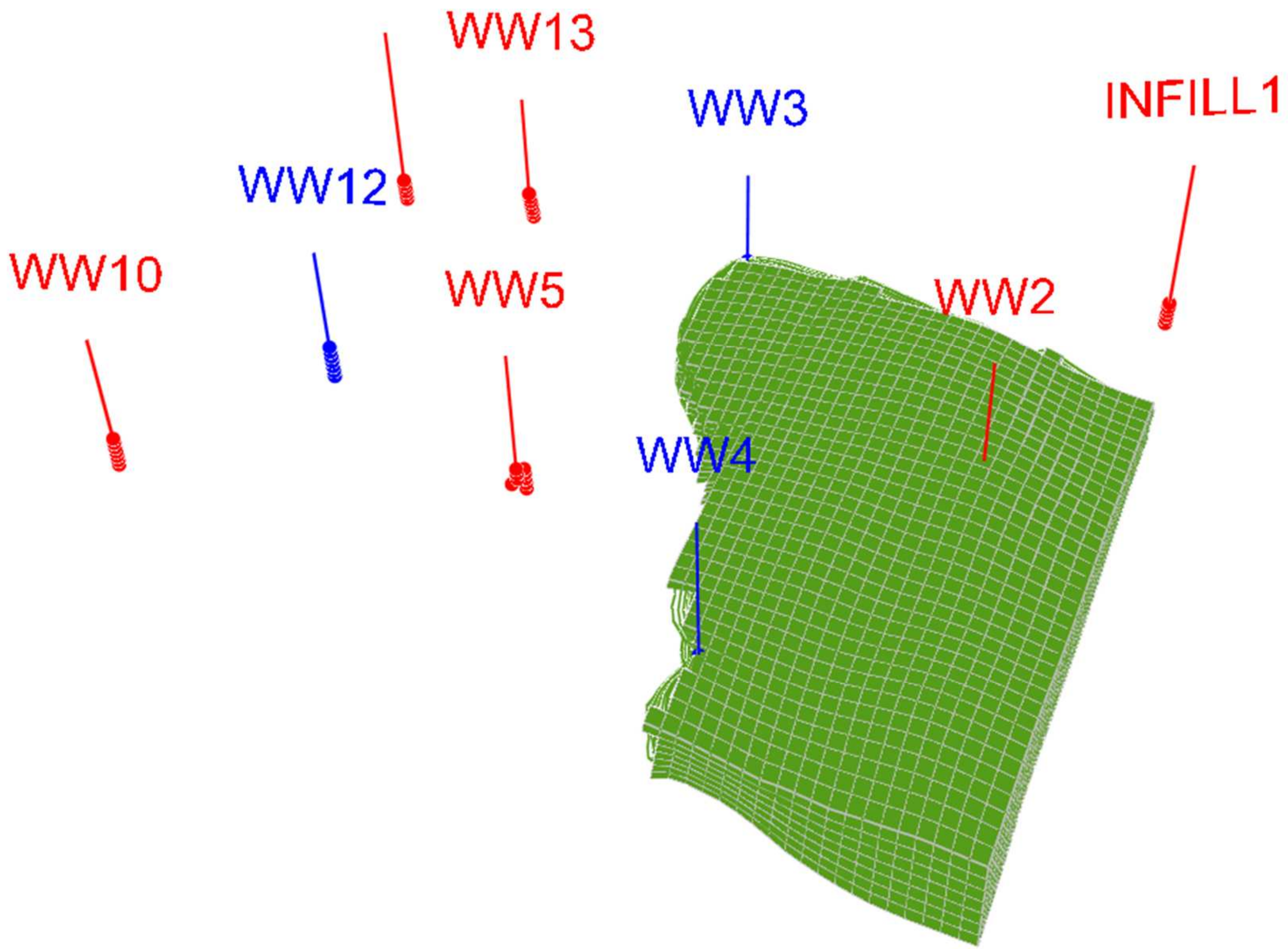
5.0E7
4.0E7
3.0E7
2.0E7
1.0E7
0.0
0
1000
2000
3000
4000
5000
Time [day]

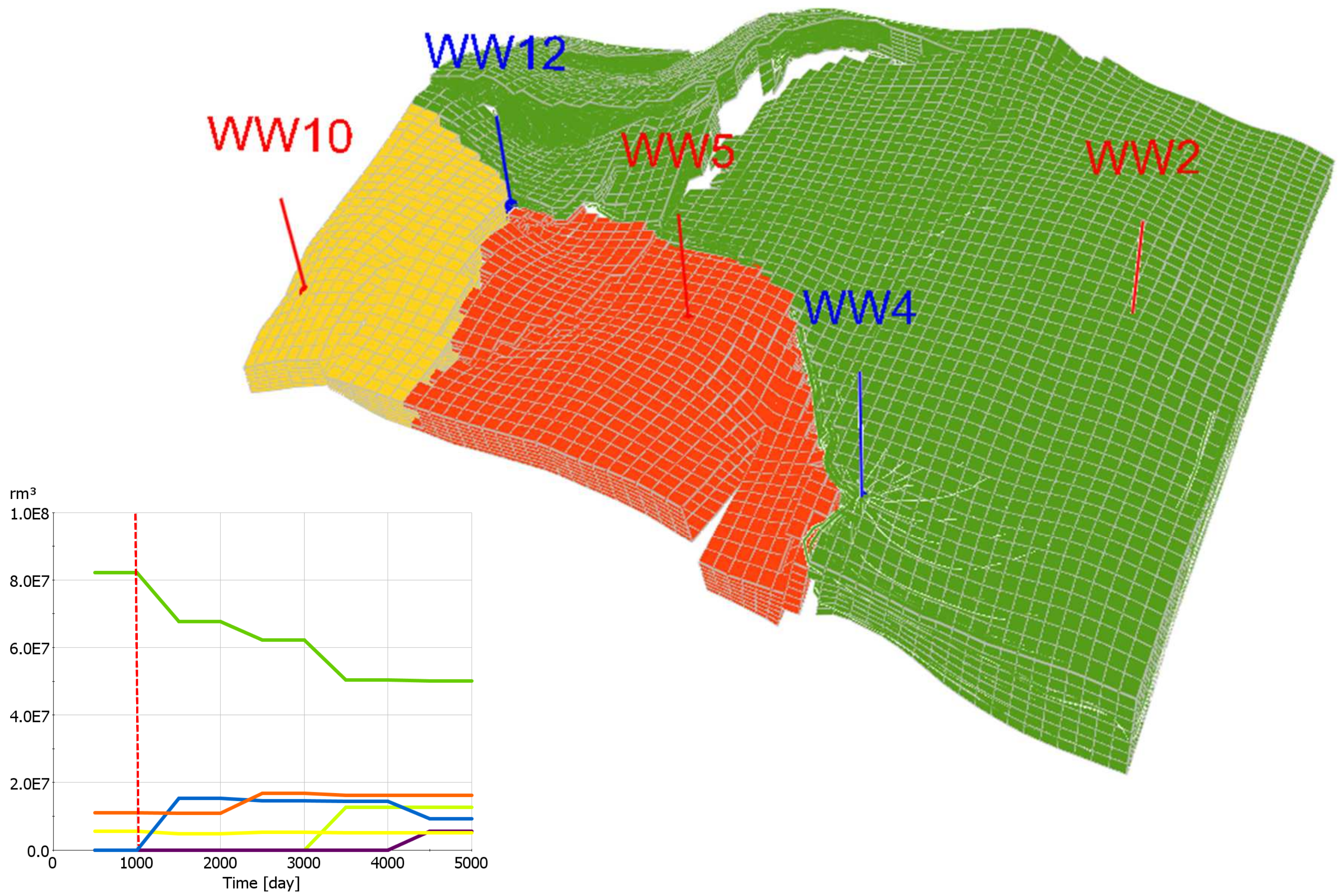
Drainage Volumes (Producers)



Drainage Volumes (Producers)

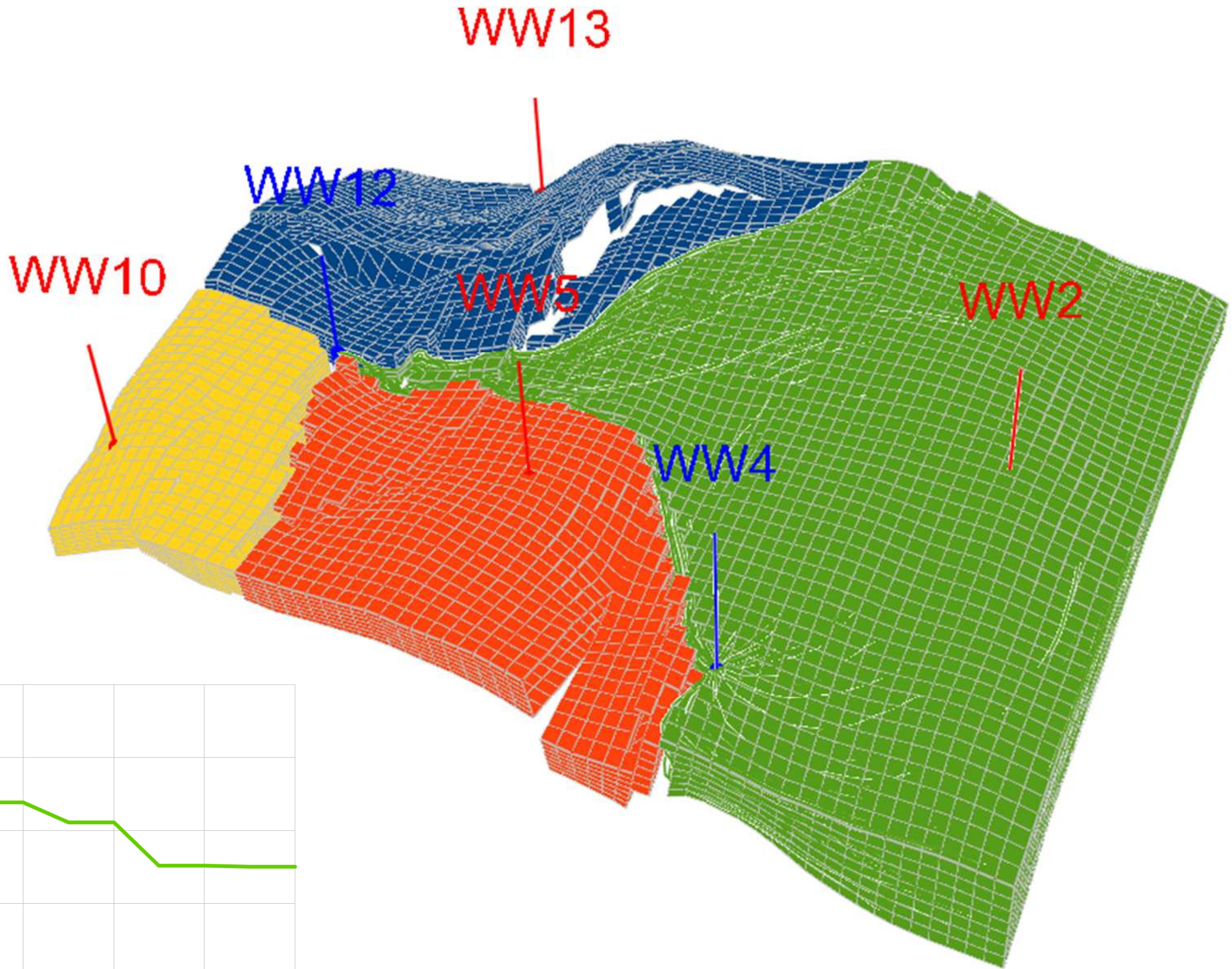


Time 1

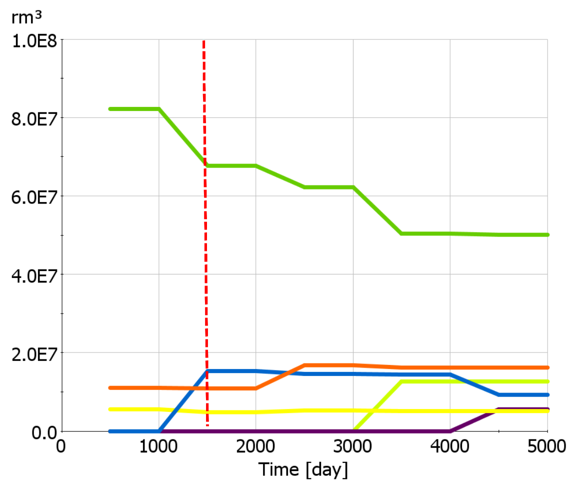


WW12
WW10
WW5
WW2
WW4
rm³
1.0E8
8.0E7
6.0E7
4.0E7
2.0E7
0.0
0
1000
2000
3000
4000
5000
Time [day]

Time 2

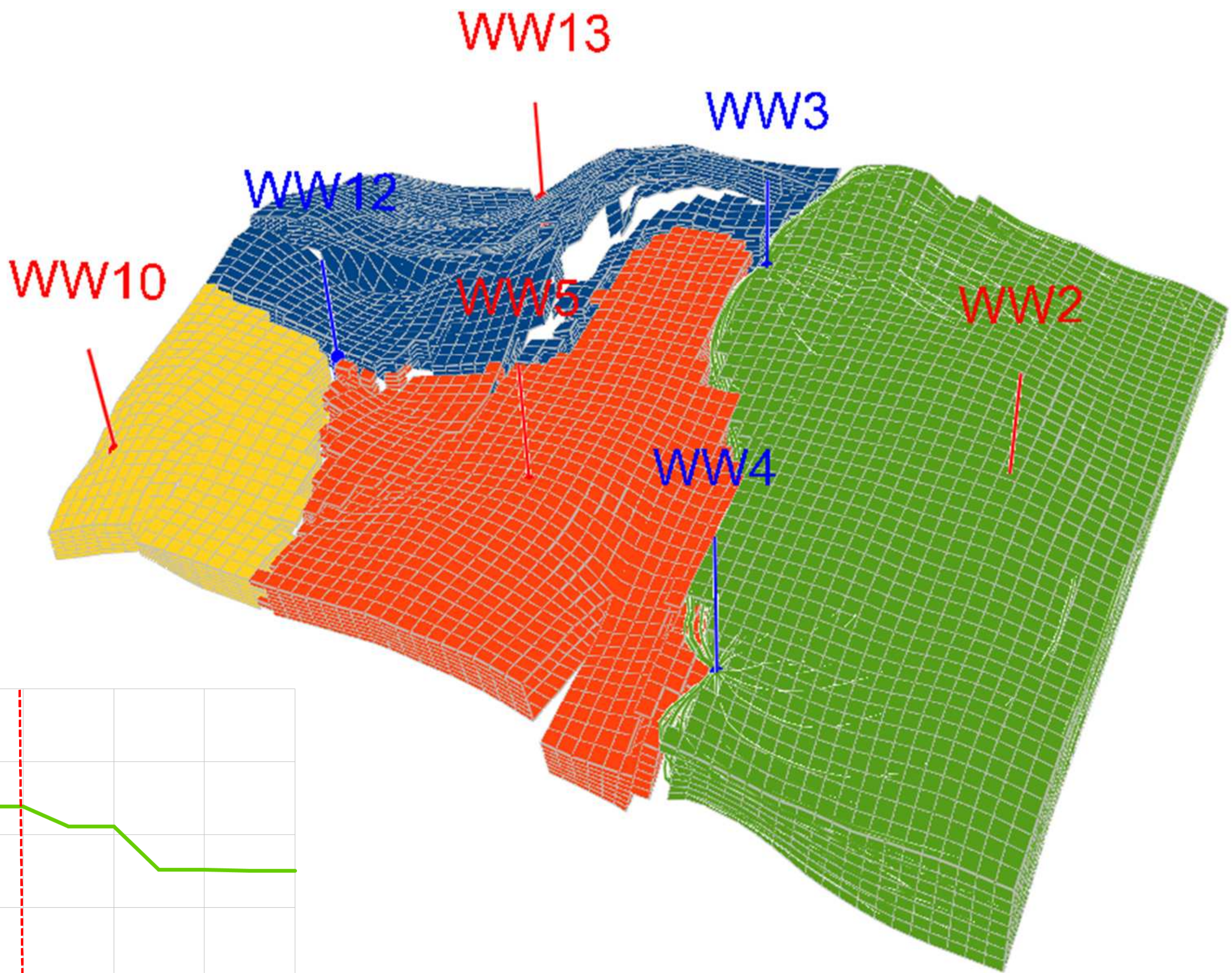


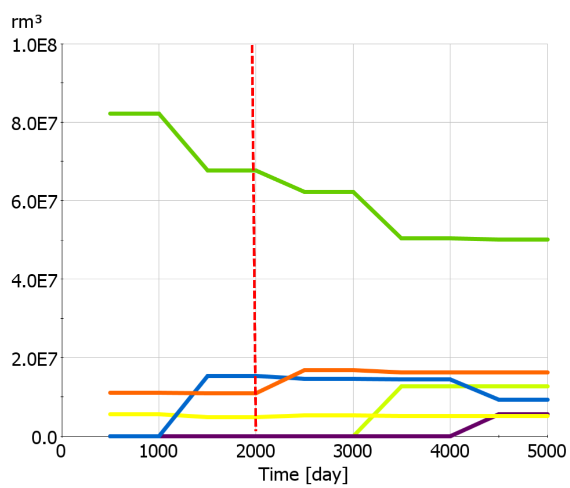
WW13
WW12
WW10
WW5
WW2
WW4



rm³
1.0E8
8.0E7
6.0E7
4.0E7
2.0E7
0.0
0
1000
2000
3000
4000
5000
Time [day]

Time 3


WW13
WW3
WW12
WW10
WW5
WW2
WW4


rm³
1.0E8
8.0E7
6.0E7
4.0E7
2.0E7
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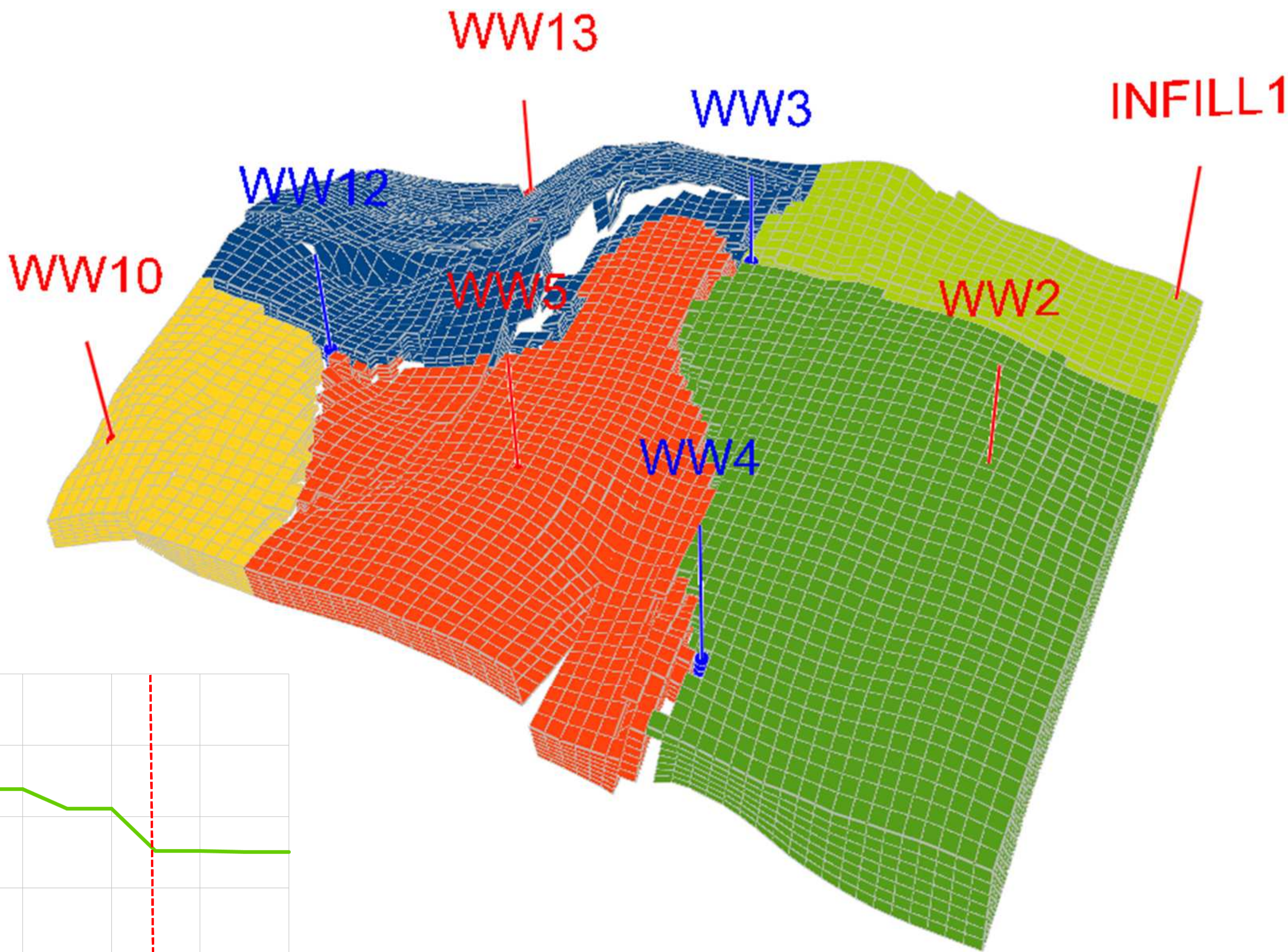
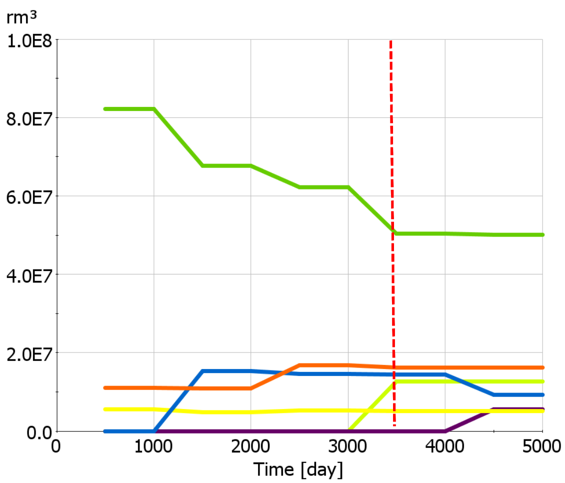
0
1000
2000
3000
4000
5000
Time [day]

Time 4


WW13
WW3
INFILL1
WW12
WW10
WW5
WW2
WW4


rm³
1.0E8
8.0E7
6.0E7
4.0E7
2.0E7
0.0
0
1000
2000
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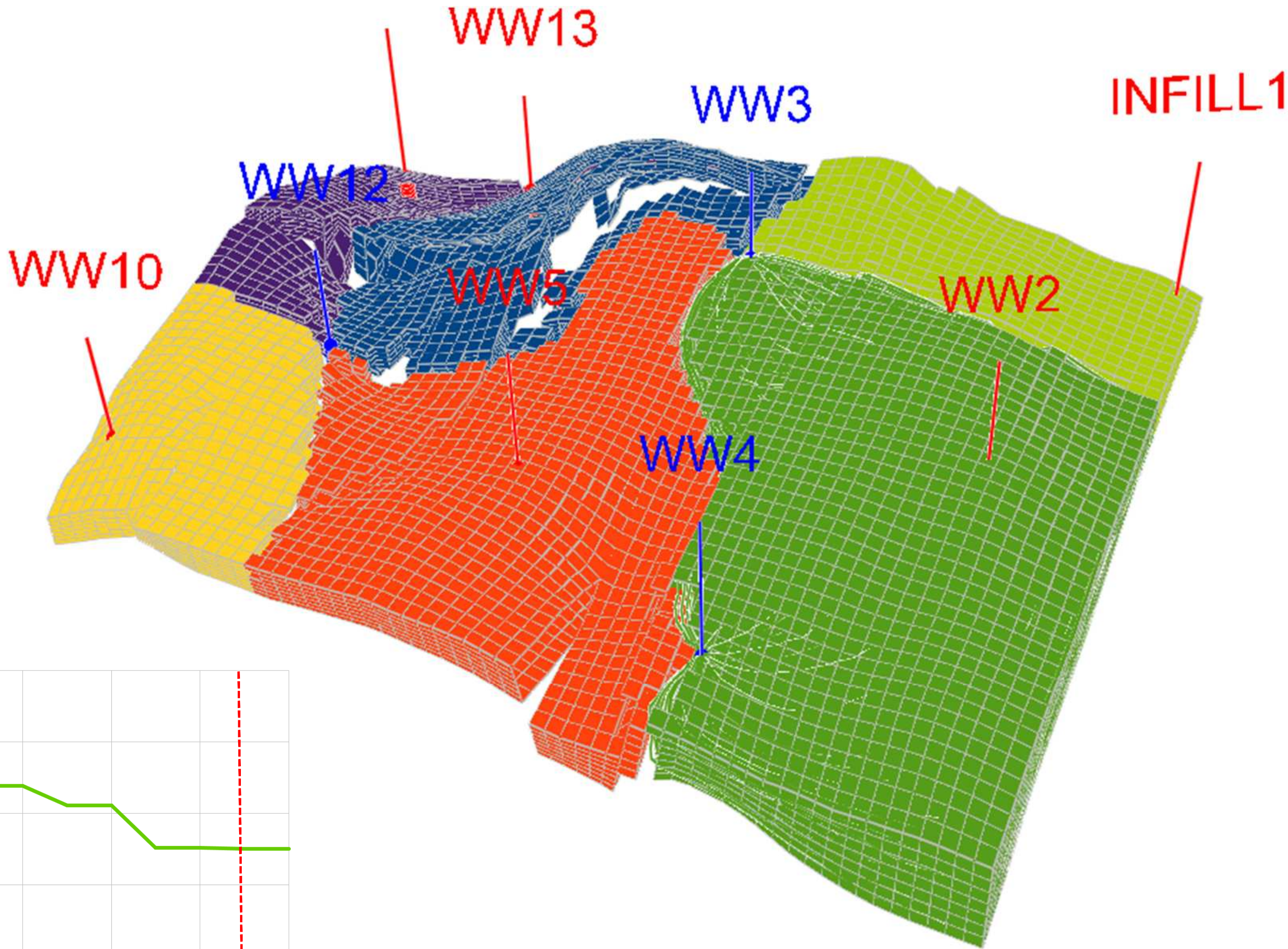
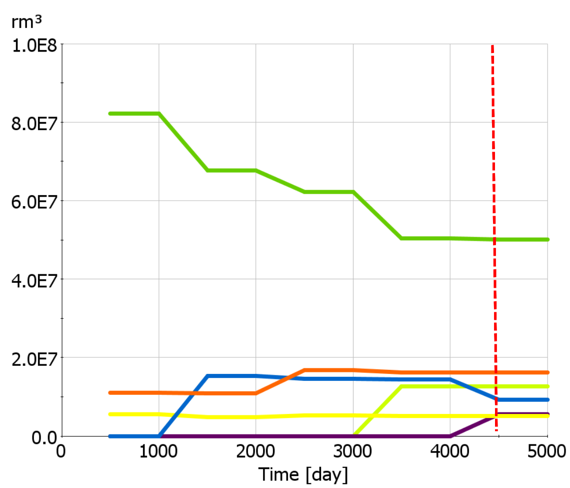
5000
Time [day]

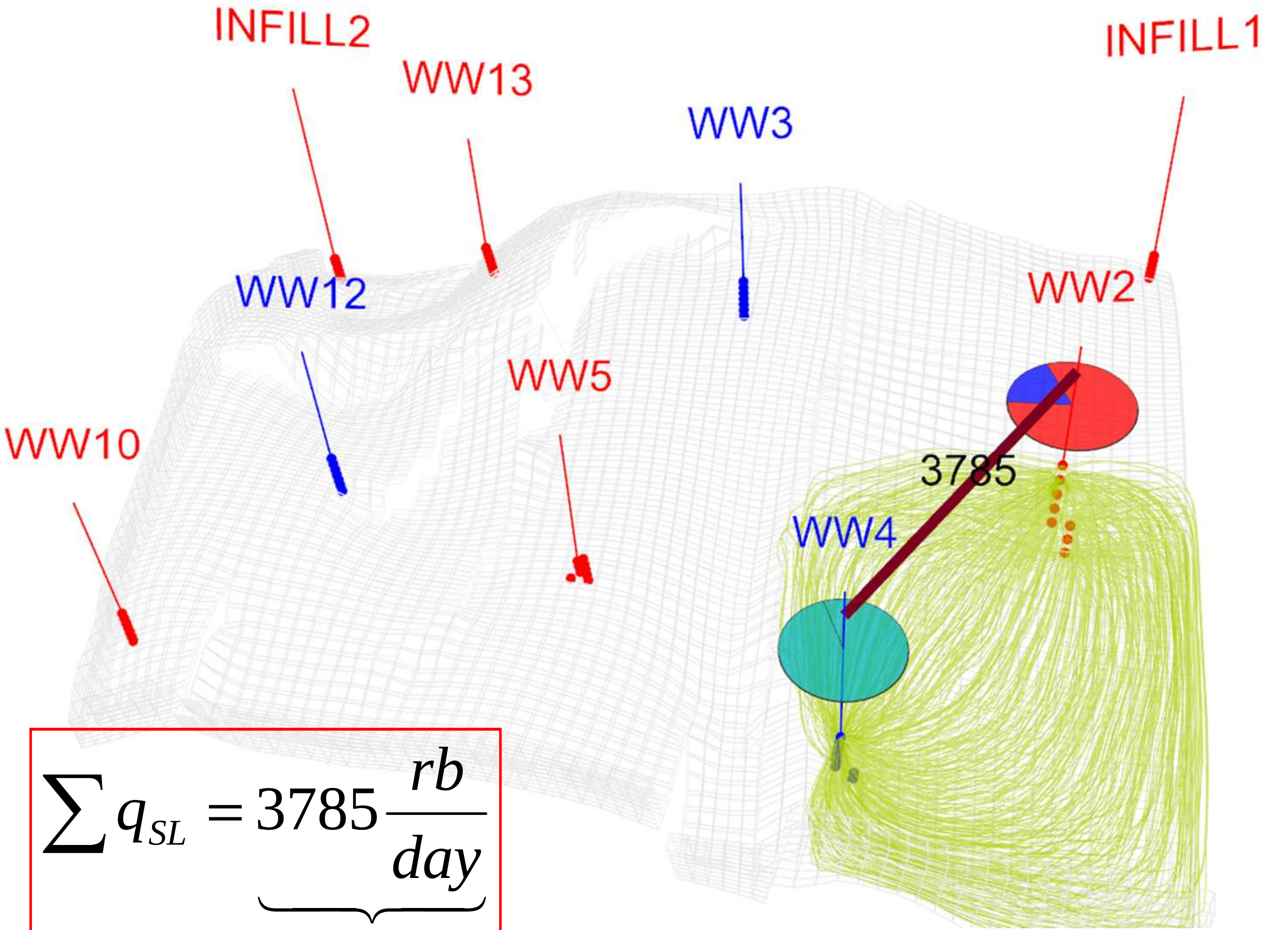
Time 5


WW13
WW3
INFILL1
WW12
WW10
WW5
WW2
WW4


rm³
1.0E8
8.0E7
6.0E7
4.0E7
2.0E7
0.0
0
1000
2000
3000
4000
5000
Time [day]

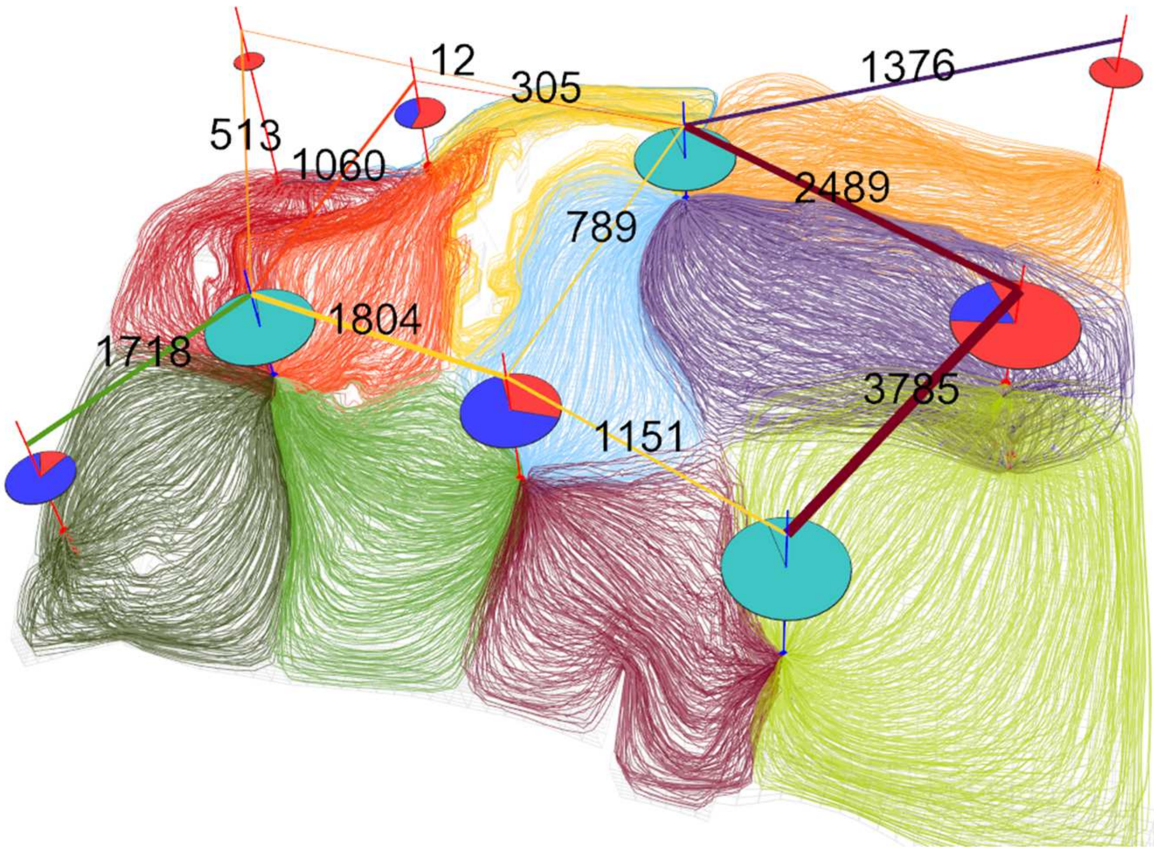
FLUX PATTERN MAPS (CONNECTIVITY)

Flux Pattern Maps

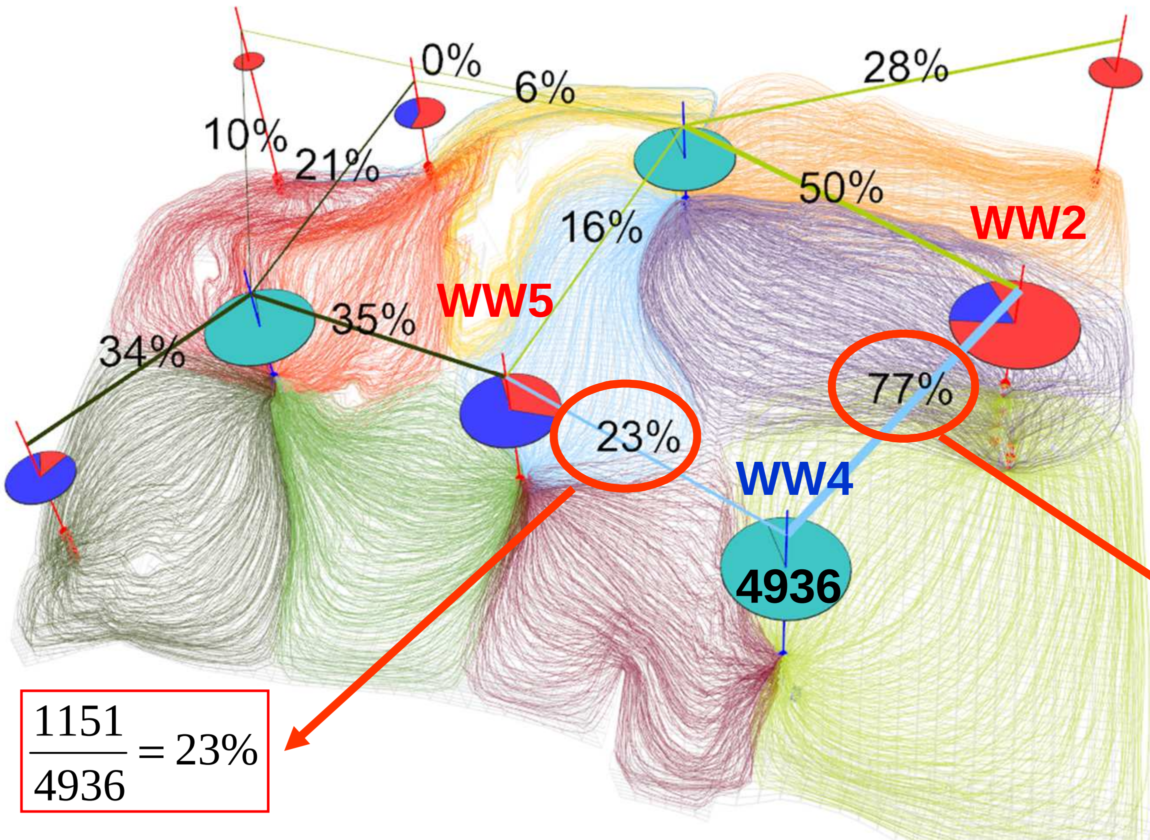


$$\underbrace{\sum q_{SL} = 3785 \frac{rb}{day}}_{\mathrm{WW4-WW2}}$$

Flux Pattern Maps



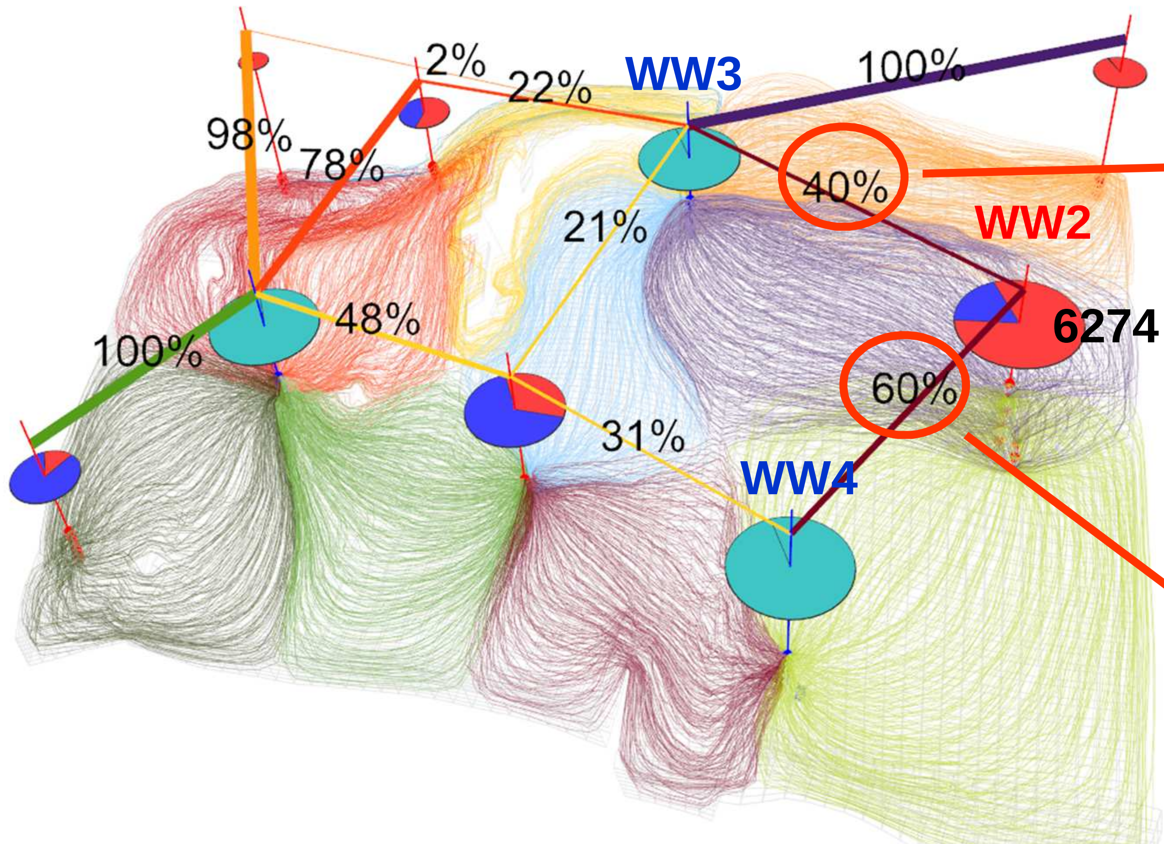
Well Allocation Factors—Injectors



$$\frac{1151}{4936} = 23\%$$

$$\frac{3785}{4936} = 77\%$$

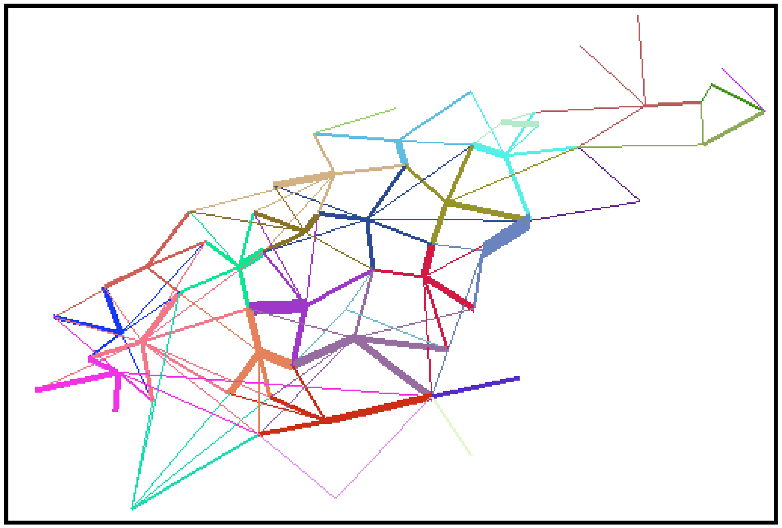
Well Allocation Factors—Producers



$$\frac{2489}{6274} = 40\%$$

$$\frac{3785}{6274} = 60\%$$

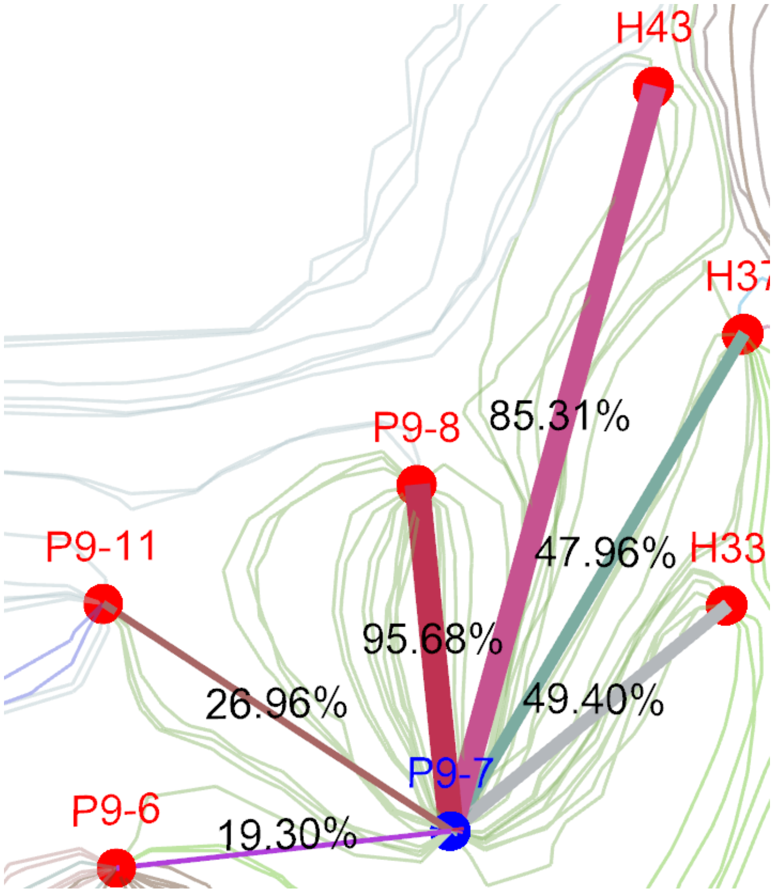
FP Maps Are Complicated



FP maps can be complicated. Impossible to deduce this type of dynamic connectivity through "fixed" pattern methods.

FLOOD SURVEILLANCE

Mining SL Connectivity Data



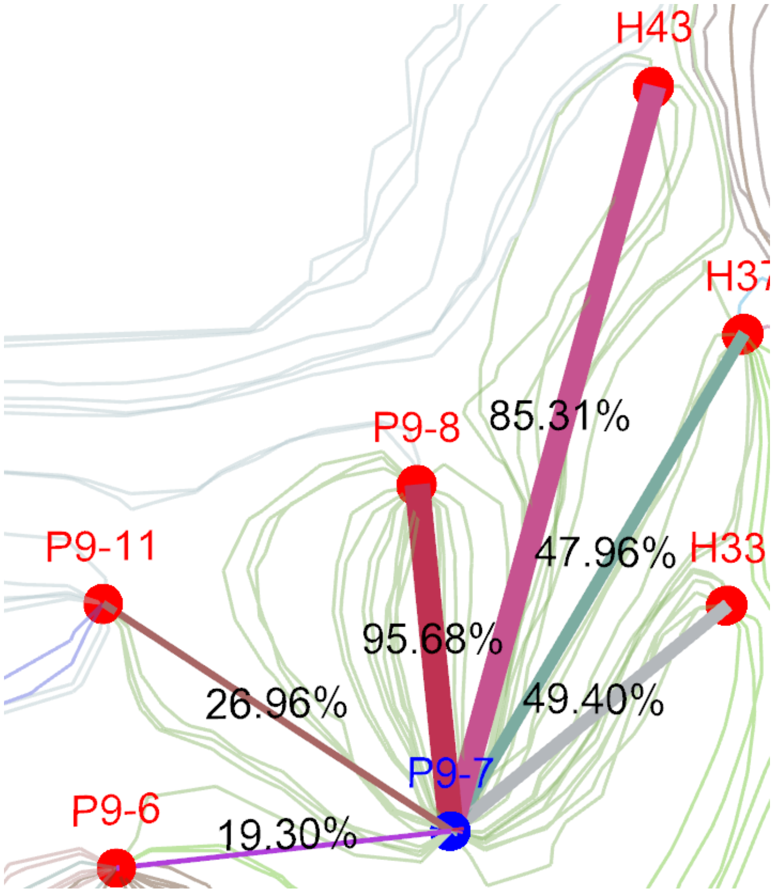
Pattern=Injector + connected off-set producers (from SL's)

Use weighted average to back-allocate oil production to injector.

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

"Surveillance"

Mining SL Connectivity Data



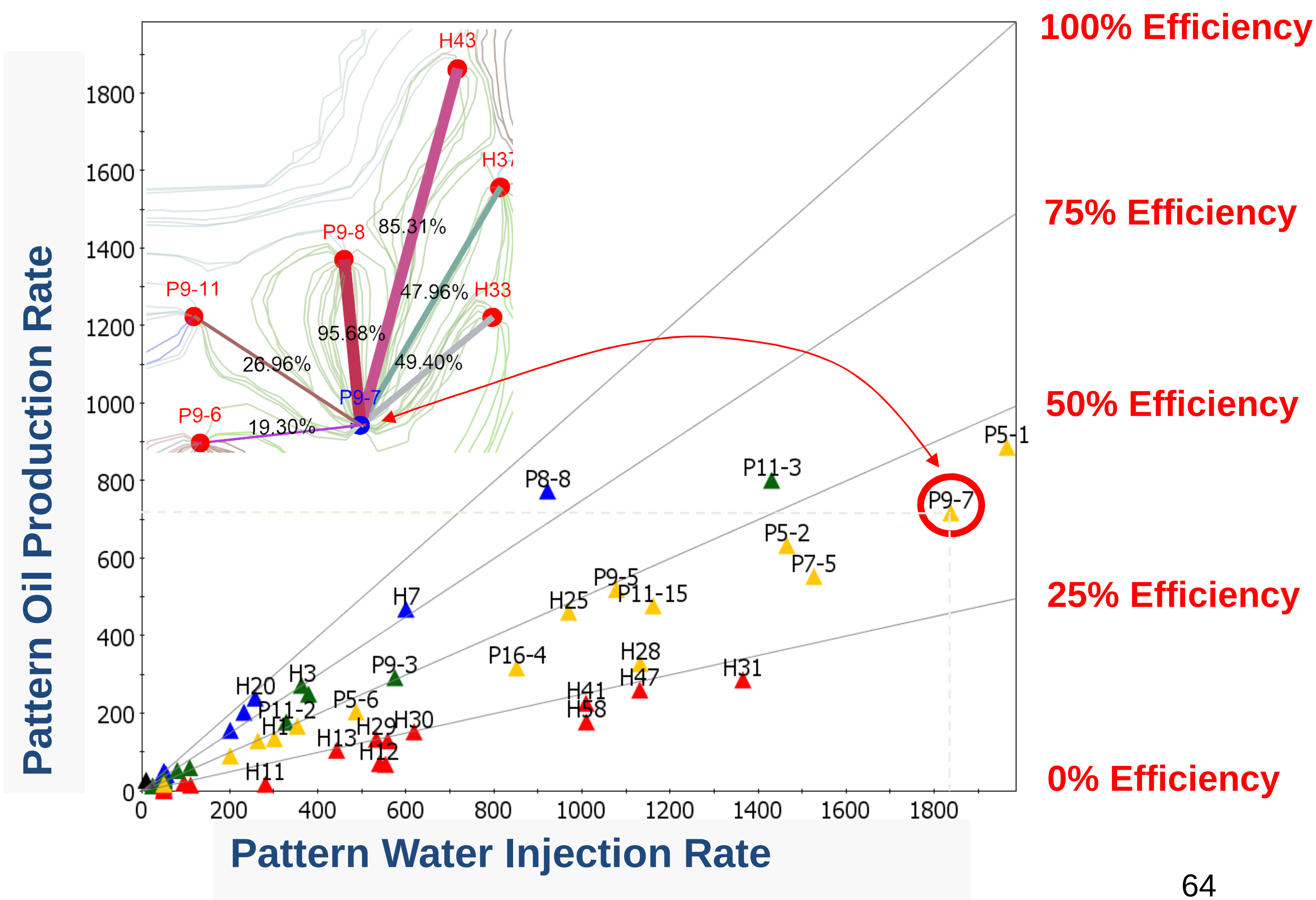
Pattern=Injector + connected off-set producers (from SL's)

Explicitly calculate the oil rate for each streamline and find Inj-Prod value (requires history matching).

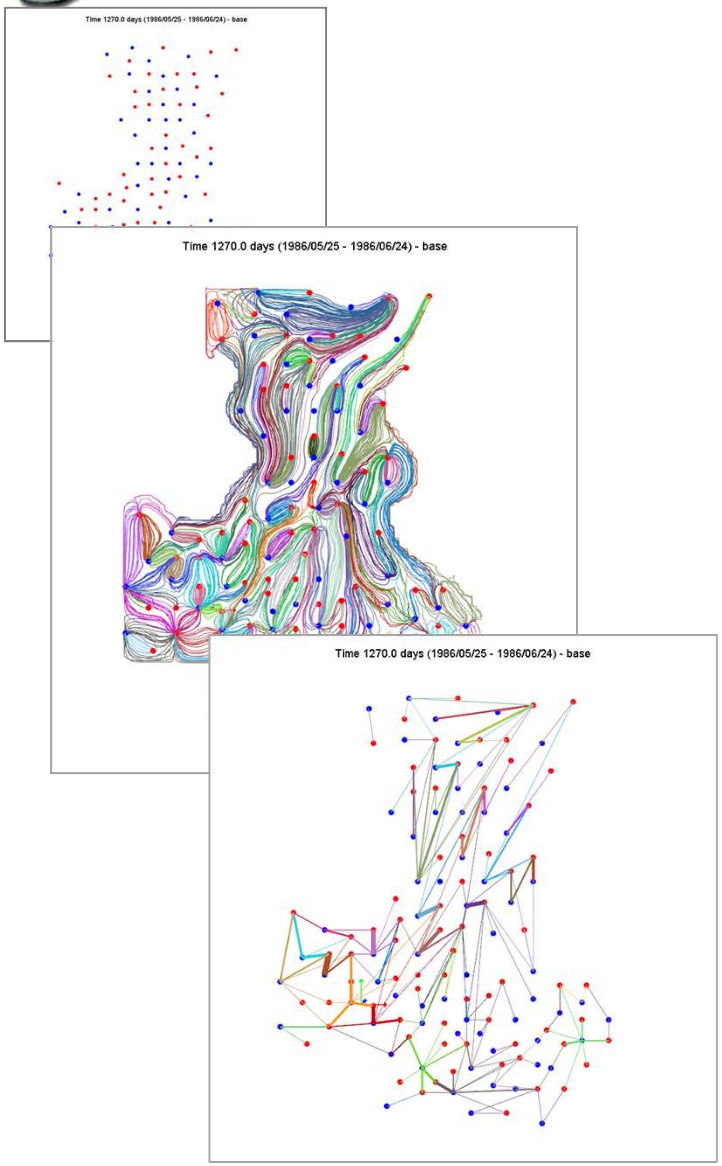
$$Q_o^{P9-7} = Q_o^{P9-7/P9-6} + Q_o^{P9-7/P9-11} + Q_o^{P9-7/P9-8} + Q_o^{P9-7/H43} + Q_o^{P9-7/H37} + Q_o^{P9-7/H33}$$

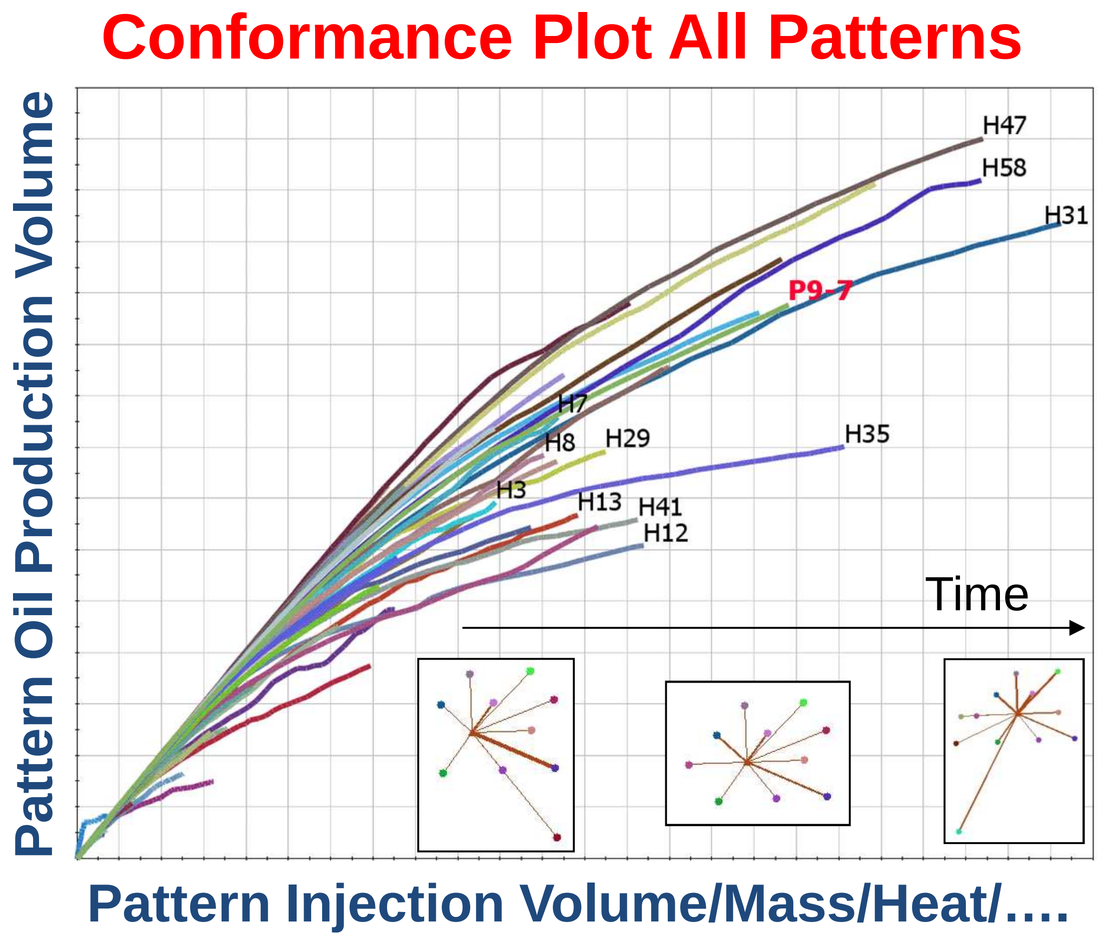
"Simulation"

The Pattern Efficiency Plot

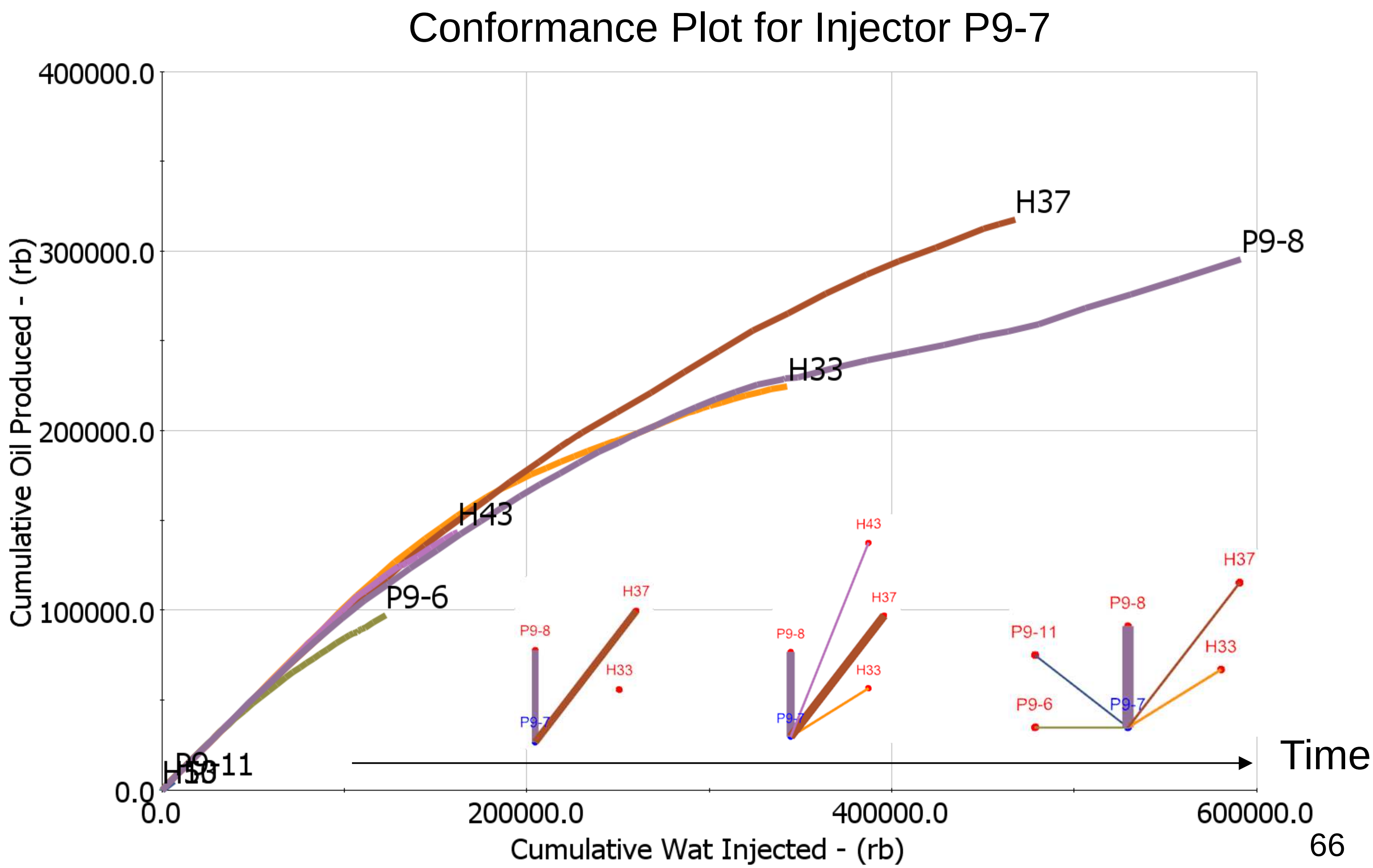


Conformance Plot—All Patterns





Per Pattern Conformance Plot



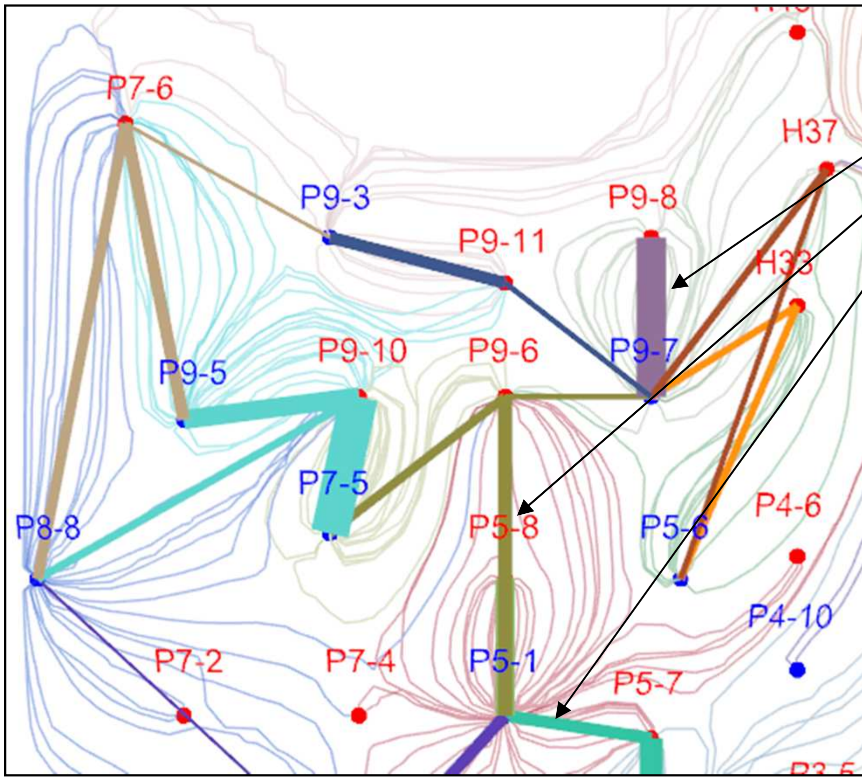
Flood Surveillance

- Surveillance is not a “simulation” model
  - Uses SL geometries to calculate WAF’s
  - Back-allocates production data to injectors
  - No predictive capabilities
  - Computationally light
- Powerful per pattern metrics
  - Pattern efficiencies and conformance plots
  - Pattern volumes

MANAGING FLOODS

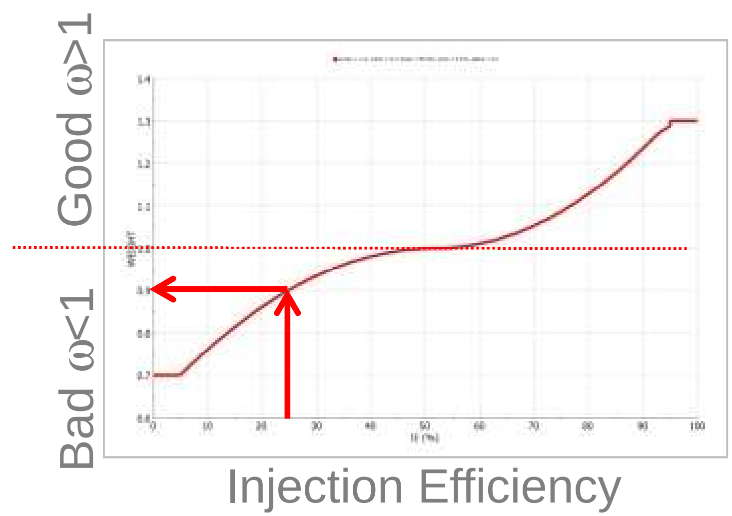
Managing Brown Fields w/ SL's

- Strengthen good connections, demote connections via a weighting function:



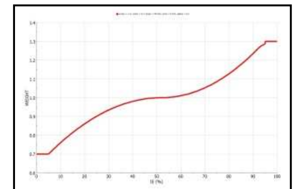
For each connection determine:

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



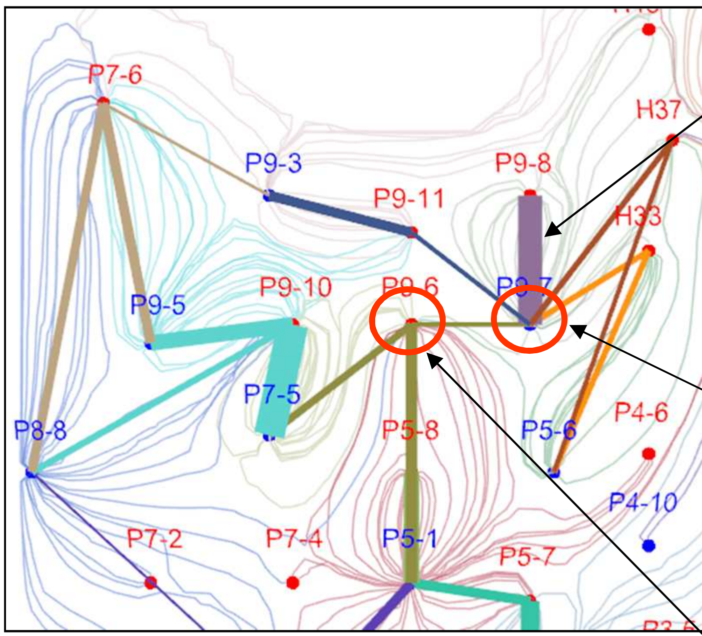
New Target Rates *(SPEREE 4/06)*

weighting function



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

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



New Injection Rate
(sum all connections)

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

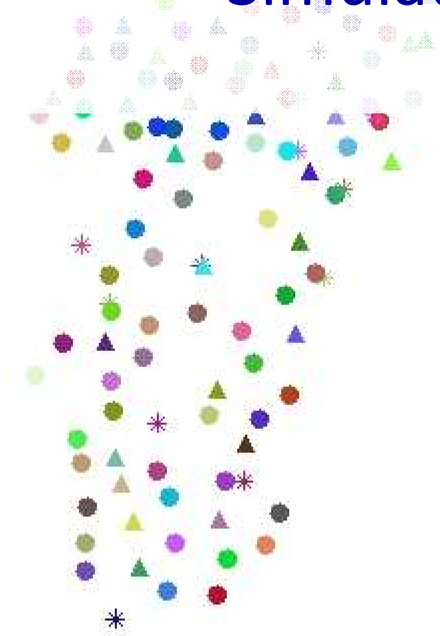
New Production Rate
(sum all connections)

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

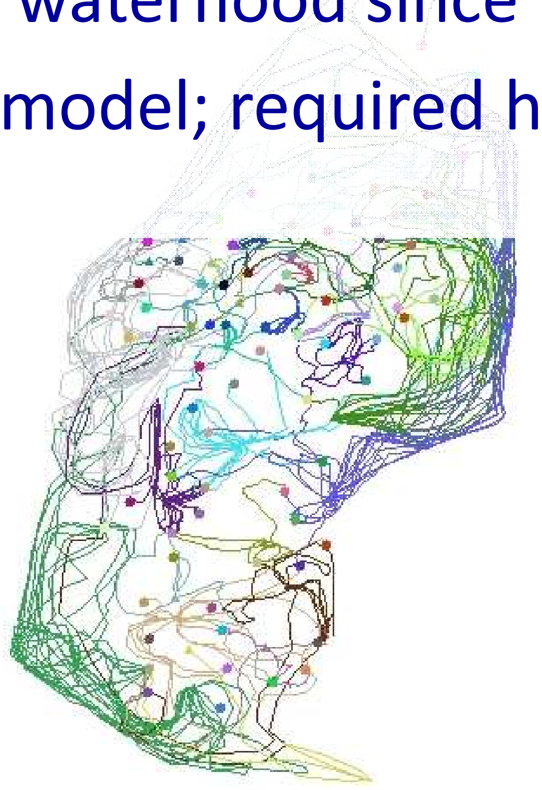
Thiele, M.R. and Batycky, R.P.; "Using Streamline-Derived Injection Efficiencies for Improved Waterflood Management," SPEREE April 2006, Vol 9, No 2, pp187-196.

Example: Thulielat Waterflood

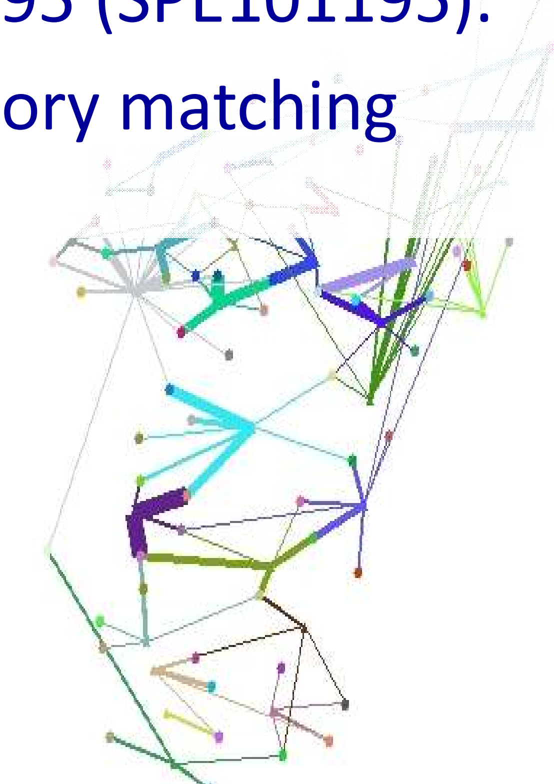
- Thulielat heavy-oil waterflood, South Oman,
  - 100+ wells, waterflood since 1995 (SPE101195).
  - Simulation model; required history matching



Wells (voidage)



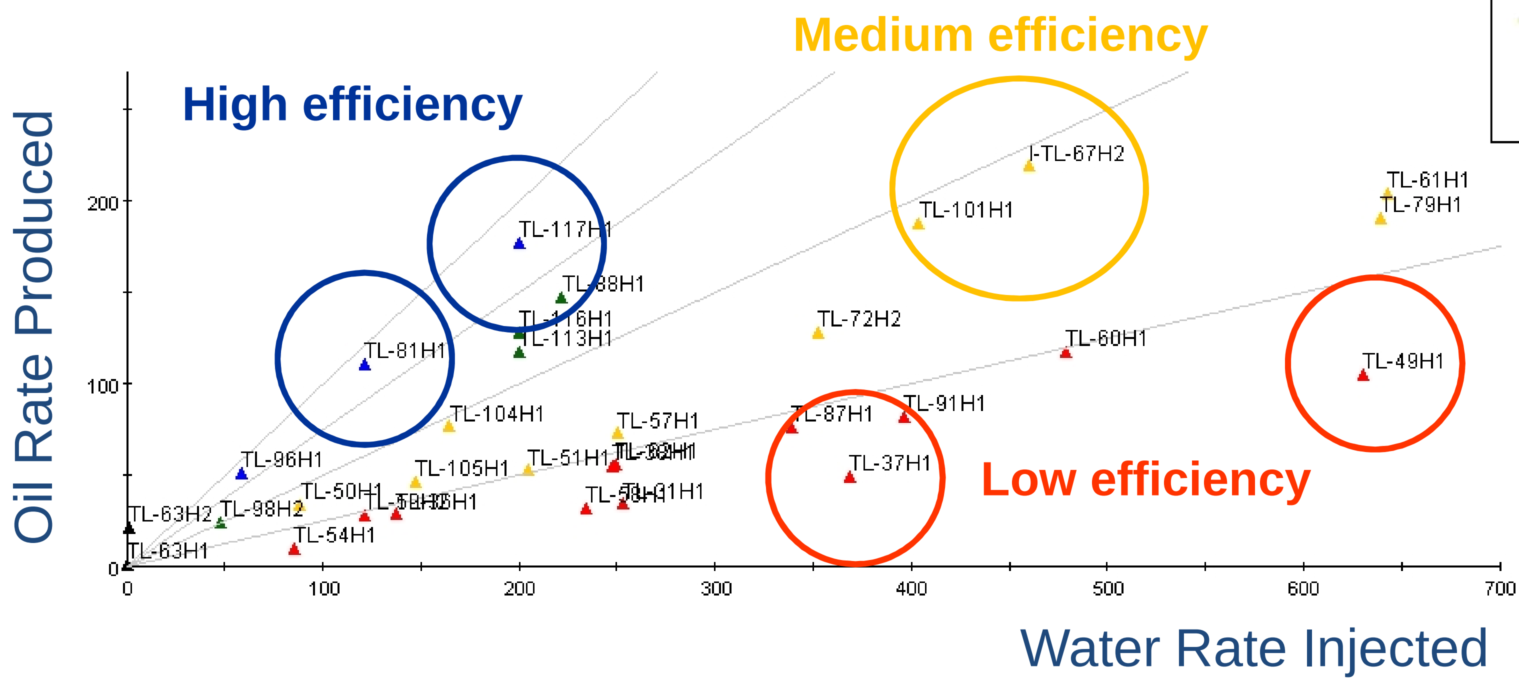
Slines

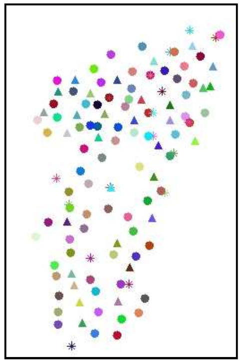


FPmap

Thulielat Injection Efficiency

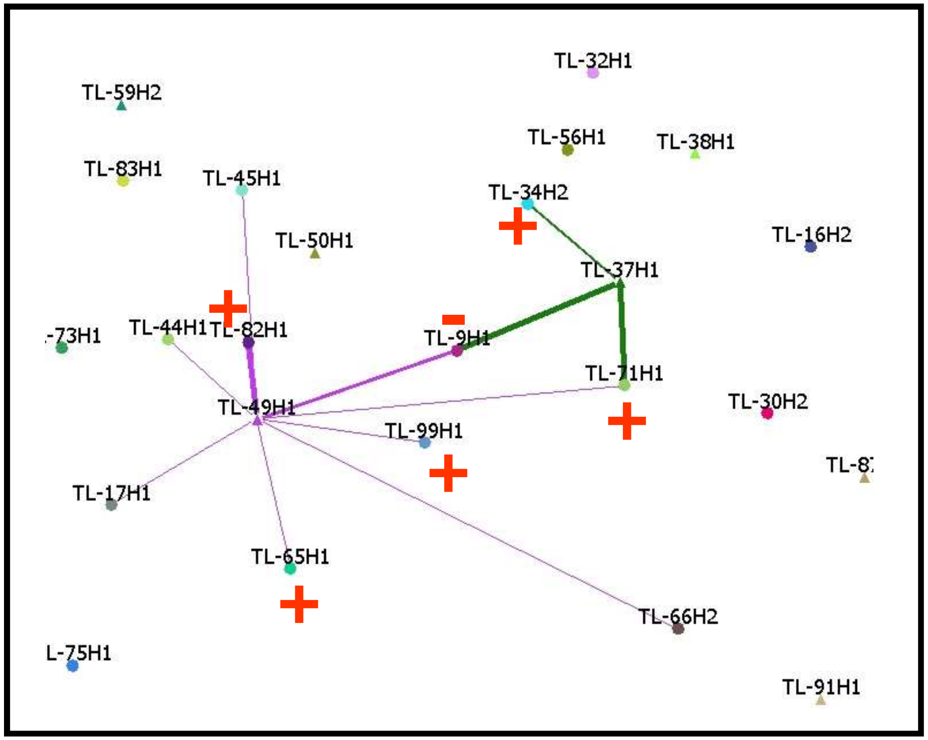
- Conformance & IE plot = current state of the reservoir



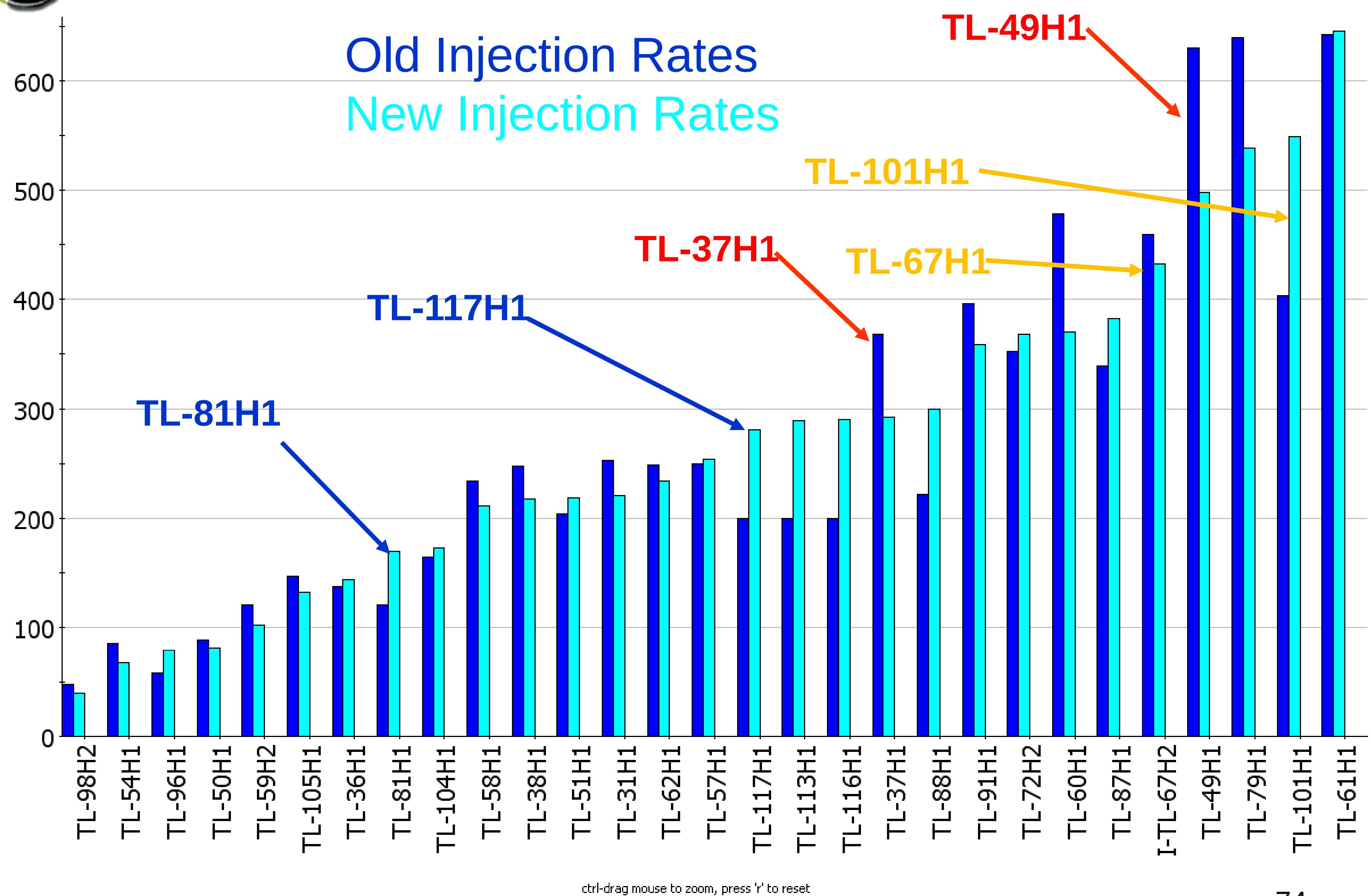


Thulielat Application

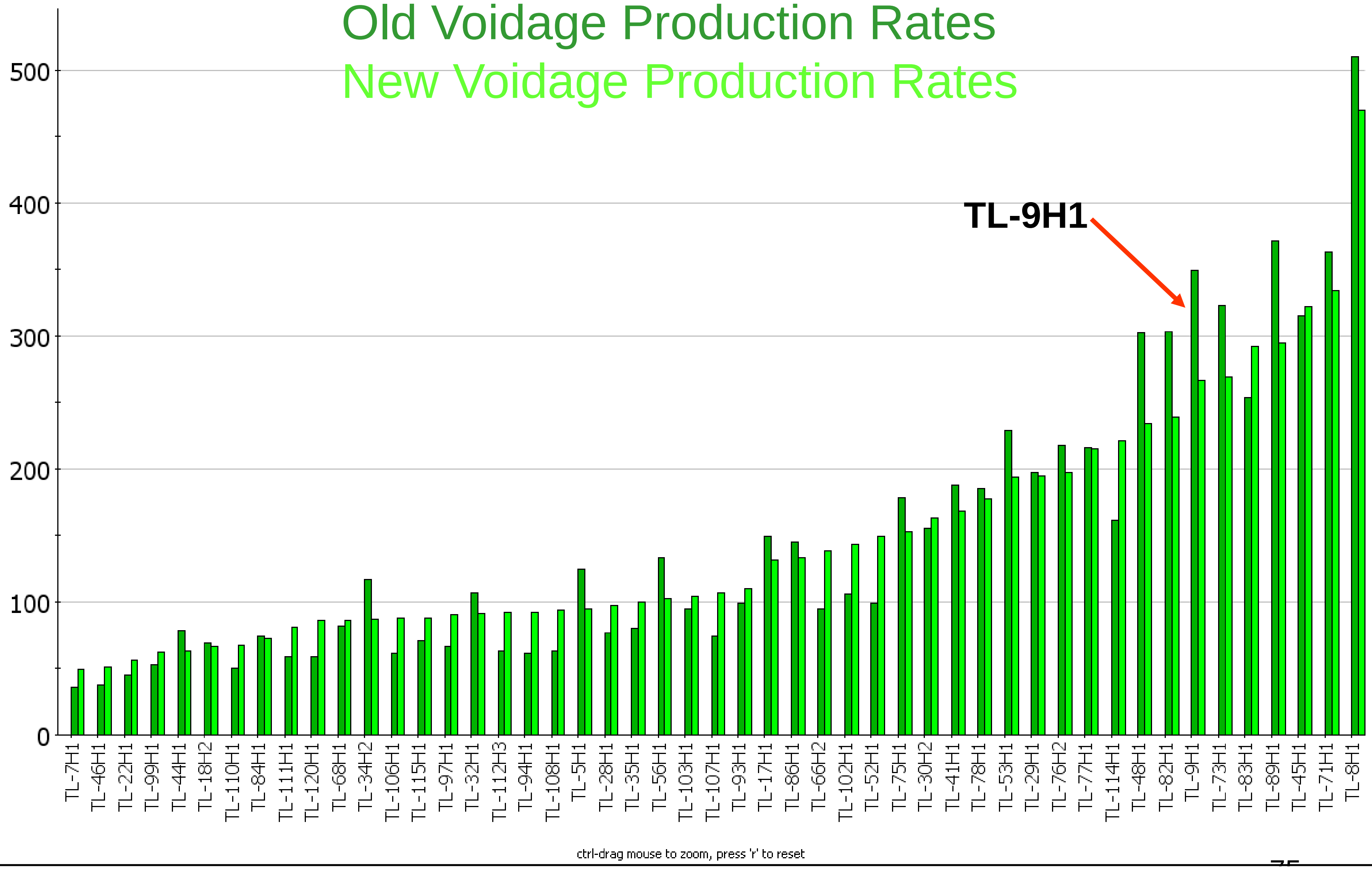
- TL-49 & TL-37 are low IE injectors→support high water rate well TL-9.



Injection Target Rates



Production Target Rates



Reservoir Management

- Use streamline-derived connection efficiencies to help set fluid target rates
    - If *simulation model*, need to history match; then use SLs to forecast by repeatedly updating target rates.
    - If *surveillance model*, then can only set target rates for one period, wait for reservoir response, then repeat.

EXTENDING APPLICABILITY OF STREAMLINE SIMULATION

IOR/EOR Concepts

- IOR—Improve sweep
  - Mobility control
  - Improved pattern balancing
  - Rate optimization
  - Infill wells / horizontals
- EOR—Mobilize trapped oil
  - Miscible flooding
  - SP/ASP/solvents/microbial
  - Thermal

Volumetric Sweep Efficiency

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

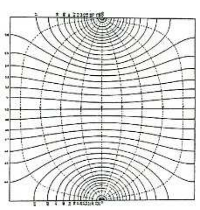
Displacement Efficiency

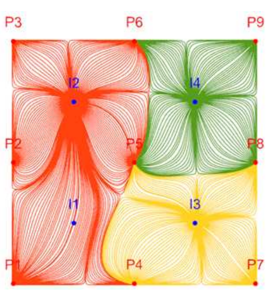
IOR

- Improve sweep using streamlines
  - Mobility control, improved pattern balancing, rate optimization, infill wells, horizontals…

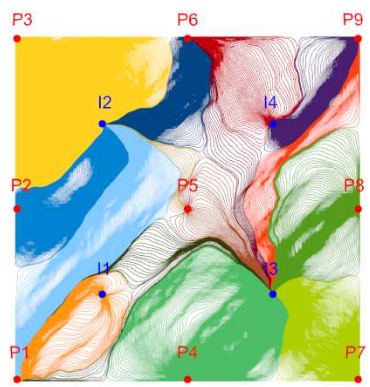
$$N_p = E_D \times \boxed{E_V} \times N$$

2D, steady state, homogenous

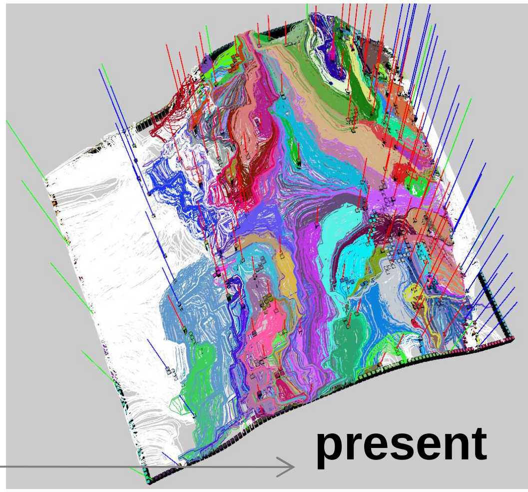




2D, SS, heterogenous



3D, heterogenous, compressible,gravity,…



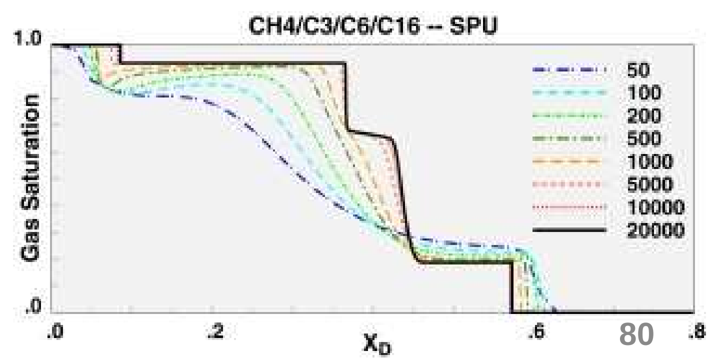
‘30 **‘60** **‘80** **present**

EOR

- Mobilize trapped oil

$$N_p = \boxed{E_D} \times E_V \times N$$

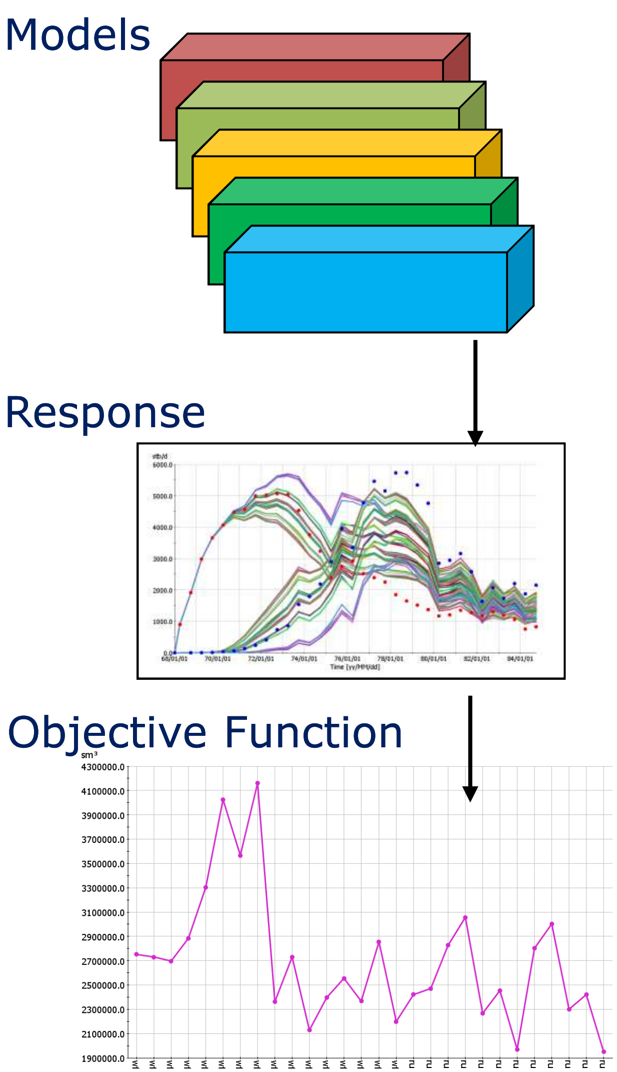
  - Miscible flooding:
    - Locally Sor→0 above MMP, but serious issues with channeling/fingering of injectant due to reservoir connectivity
  - SP/ASP/solvents/microbial
    - Drive M-ratio and Sor down; key is to properly engineer concentrations/slug sizes
  - Thermal
    - Drive M-ratio and Sor down; key is delivery of heat to the reservoir by conduction and diffusion; steam flooding issues with condensation; ISC keeping front burning by proper air supply.



Areas of Applicability

- Improve management of on-going floods.
  - Most immediate application.
- Ranking, screening, & uncertainty estimation
  - Fast proxy able to capture dynamic connectivity.
  - Interested in the response of an ensemble of reservoir models.
- History Matching
  - Use SL to identify areas of the reservoir to modify.
  - Road to “geologically” consistent model calibration.
- Enhanced Oil Recovery
  - Compositional, surfactant/polymer, thermal.
  - Very difficult problems to solve under geological uncertainty.

Ranking & Screening

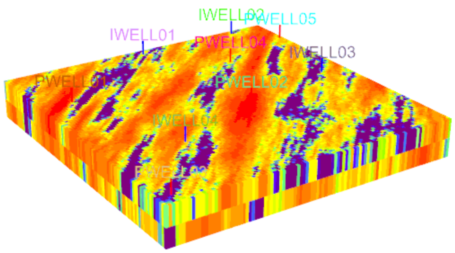


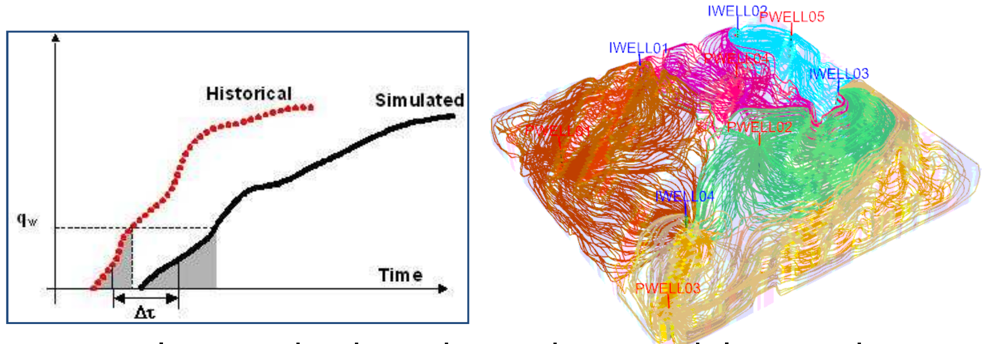
- Screening (sensitivity) runs are essential to modeling studies.
- Quantify impact of uncertainty in input parameters:
  - Geology, PVT, relperms, initialization...
  - Different forecast scenarios.
- Scenarios can grow exponentially
- Use streamlines as a fast proxy

History Matching

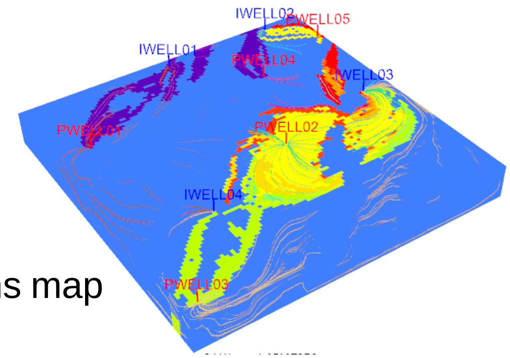
- Identify flow zones
- Identify magnitude of perm/poro change from time shift for each well
- Map "corrections" to grid using drainage volume information

Starting model





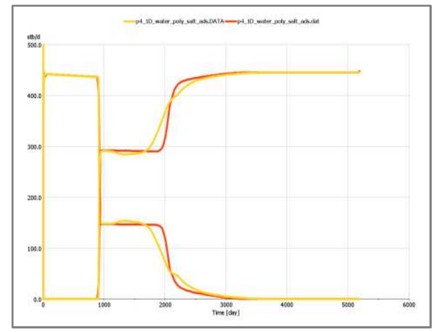
Deconvolute production mismatch to spatial corrections

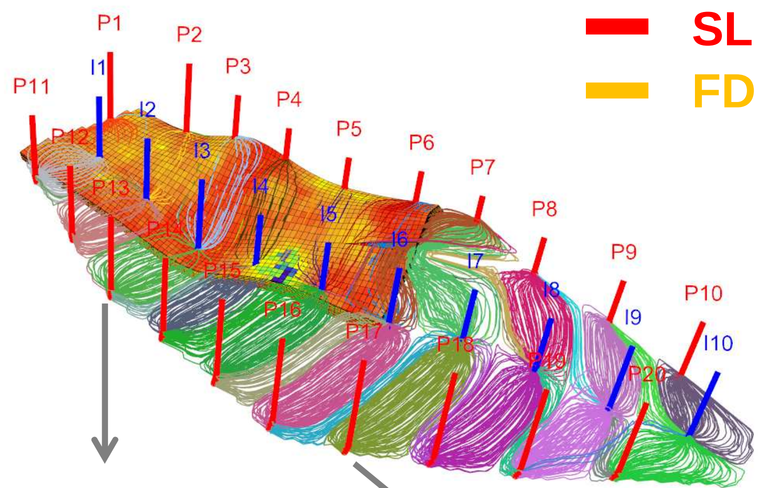


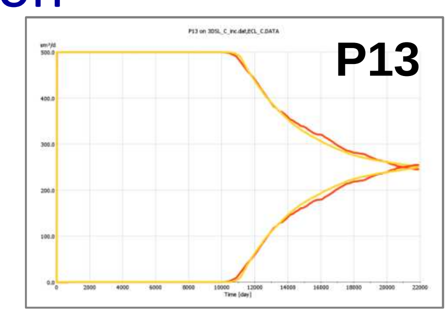
Local corrections map

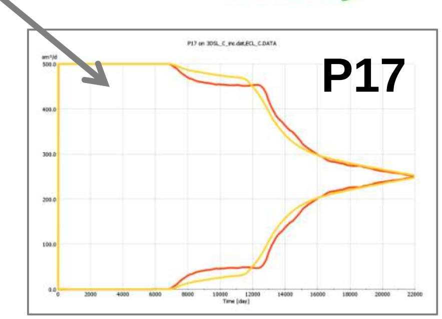
EOR/IOR

- Polymer flooding
  - 4 components: oil, water, polymer, salt
  - Water viscosity a function of polymer & salt concentrations, shear rate
  - Adsorption
  - Permeability reduction due to adsorption



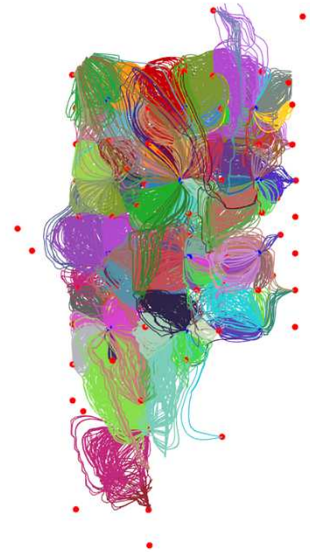




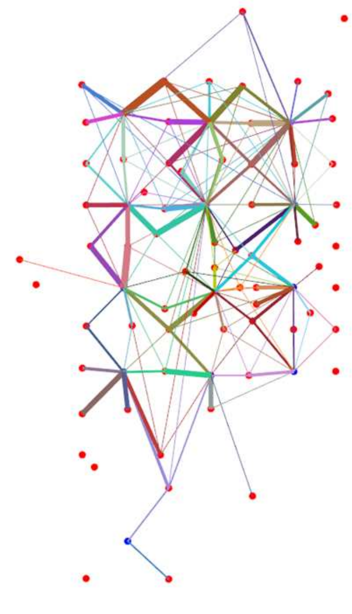


Improved Polymer-Flood Management Using Streamlines, SPEREE April 2011, (SPE 132774)

Summary/Conclusions



- SL's offer introduce two new RE metrics:
  - Dynamic drainage/irrigation volumes for each well.
  - Dynamic connectivity maps of inj/prod support.
- Patterns are now dynamic and quantifiable.
  - Injection efficiency and per-pattern conformance plots.
  - Re-allocate volumes according to



- Speed useful for workflows centered on optimization.
- Add complexity by adding flow physics along SLs.
- SLs are visually powerful; asset teams find common ground.
- But…SLs not universally applicable.

Follow-Up Reading

- Streamline Simulation (SPE 2011)—Getting Up to Speed Series (online only)
- Improved Polymer-Flood Management Using Streamlines, SPEREE April 2011, (SPE 132774)
- Streamline Simulation for Modern Reservoir-Engineering Workflows, JPT January 2010.
- Revisiting Reservoir Flood-Surveillance Methods Using Streamlines, SPEREE April 2008
- Using Streamline-Derived Injection Efficiencies for Improved Waterflood Management, SPEREE April 2006