Reduced Order Physics Capacitance Resistance Models

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Hypothesis

Characteristics of a reservoir can be inferred from analyzing production and injection data only.

CRM for an Injector-Producer Pair

Continuity:

$$c_t V_p \frac{d\bar{p}}{dt} = I(t) - q(t)$$

Production Rate:

$$q(t) = J(\bar{p} - p_{wf})$$

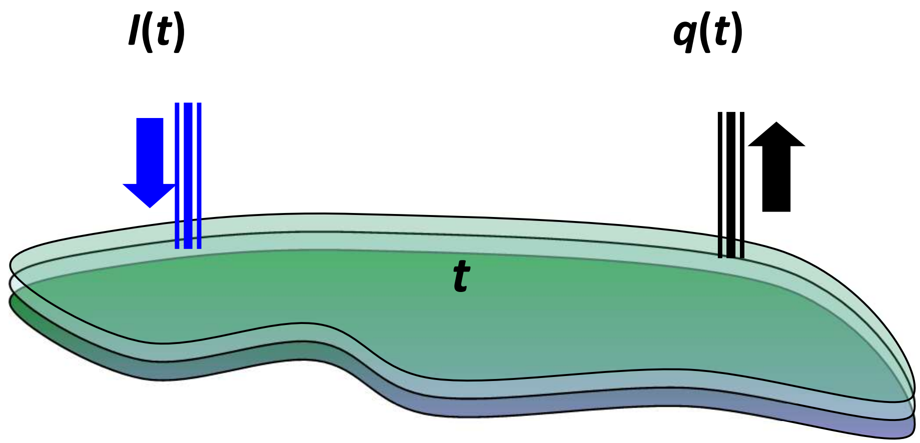
"Pressure is a reservoir engineer's best friend"
Fokert Brons

Combine to form

Ordinary Differential Equation:

$$\frac{dq(t)}{dt} + \frac{1}{\tau} q(t) = \frac{1}{\tau} I(t) - J \frac{dp_{wf}}{dt}$$

Time constant: $\tau = \dfrac{c_t V_p}{J}$



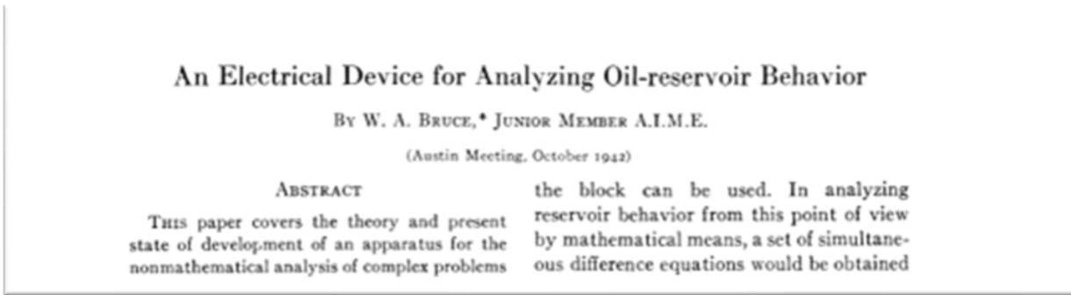
Analytic Solution

$$q(t_k) = \overbrace{q(t_{k-1}) e^{-\frac{\Delta t}{\tau}}}^{\text{Primary Production}} + \overbrace{\left(1 - e^{-\frac{\Delta t}{\tau}}\right) I(t_k)}^{\text{Injection}} \overbrace{- J\left(p_{wf}(t_k) - p_{wf}(t_{k-1})\right) e^{-\frac{\Delta t}{\tau}}}^{\text{BH pressure change}}$$

novel idea for a persistent allenge in reservoir engineering… ack of geologic data

Bruce (1943)

SPE 414, Wahl et al. (1962)


An Electrical Device for Analyzing Oil-reservoir Behavior

By W. A. Bruce,* Junior Member A.I.M.E.

(Austin Meeting, October 1942)

Abstract

This paper covers the theory and present state of development of an apparatus for the nonmathematical analysis of complex problems the block can be used. In analyzing reservoir behavior from this point of view by mathematical means, a set of simultaneous difference equations would be obtained

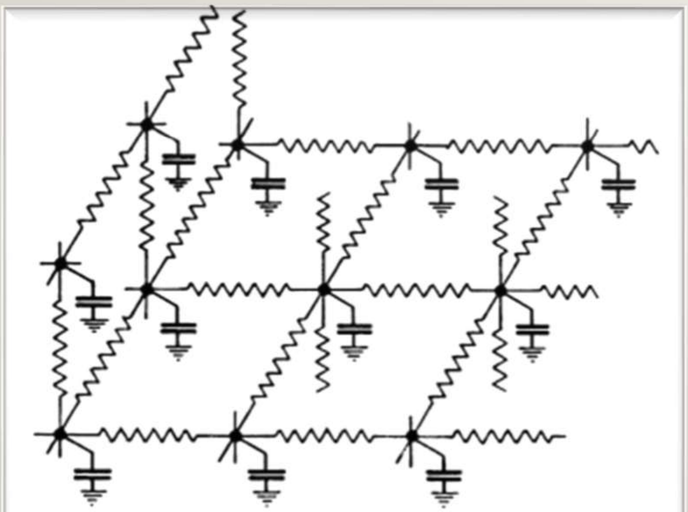


Fig. 3.—Part of three-dimensional electrical representatio

Matching the Performance of Saudi Arabian Oil Fields

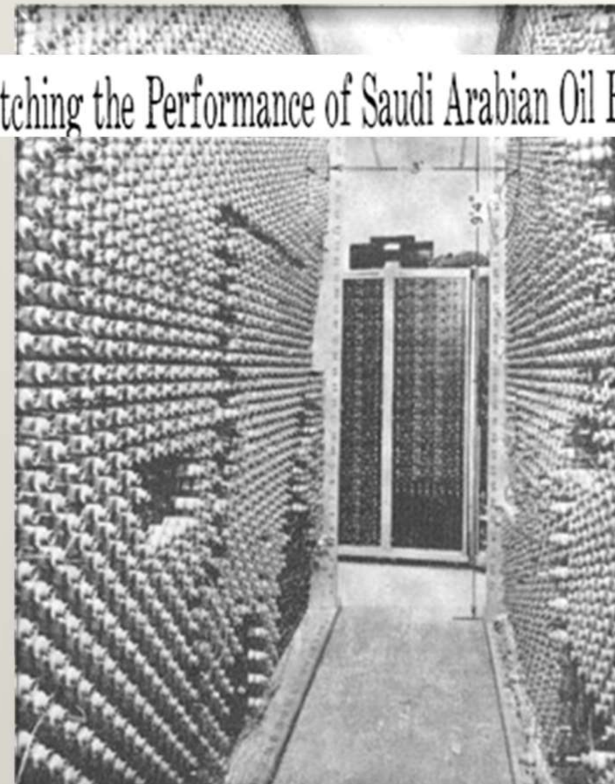


Fig. 1—Inside View of "Tunnel" Formed b the Two Sections of the Model's Resistor-

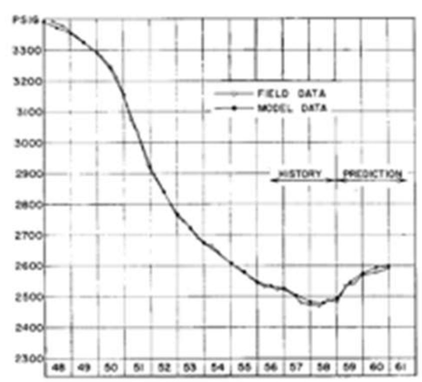


Fig. 14—Comparison of Model Pressure and Field Pressure for Controller 4, Northern Abqaiq Field.

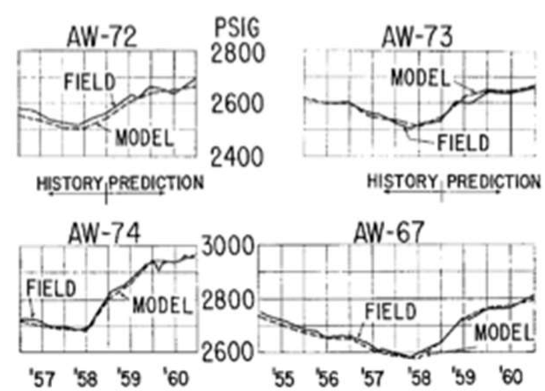
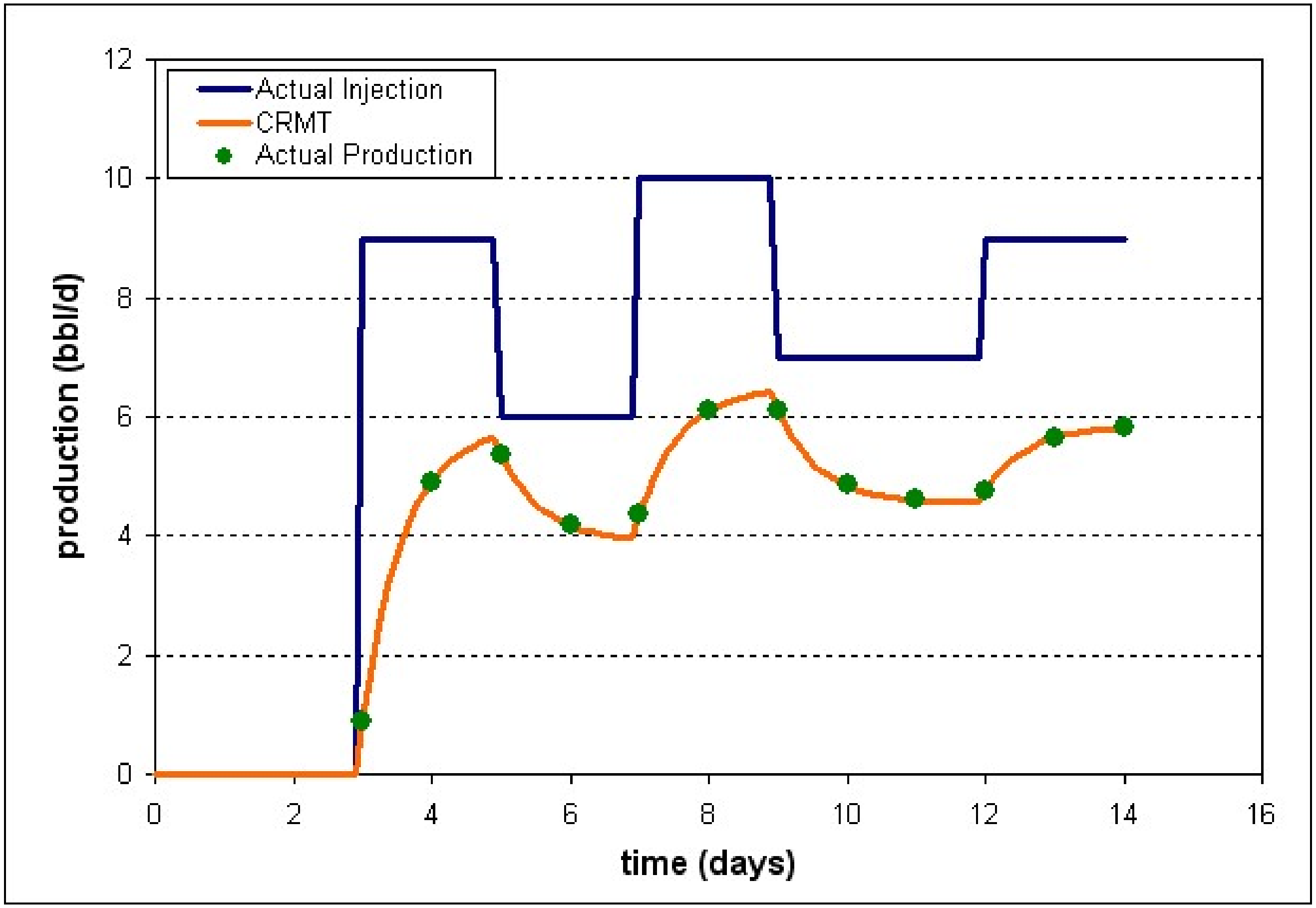


Fig. 16—Comparison of Model vs Field Bottom-Hole Pressures for Four Abqaiq Wells.

Signal Response

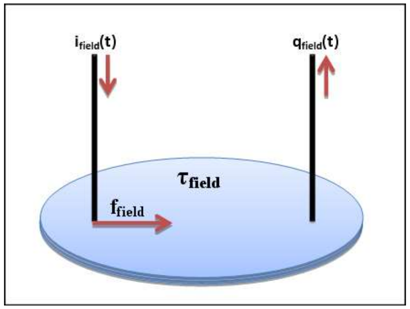
Production response to an injection signal



Connectivity

τ_{ij} = 6 days

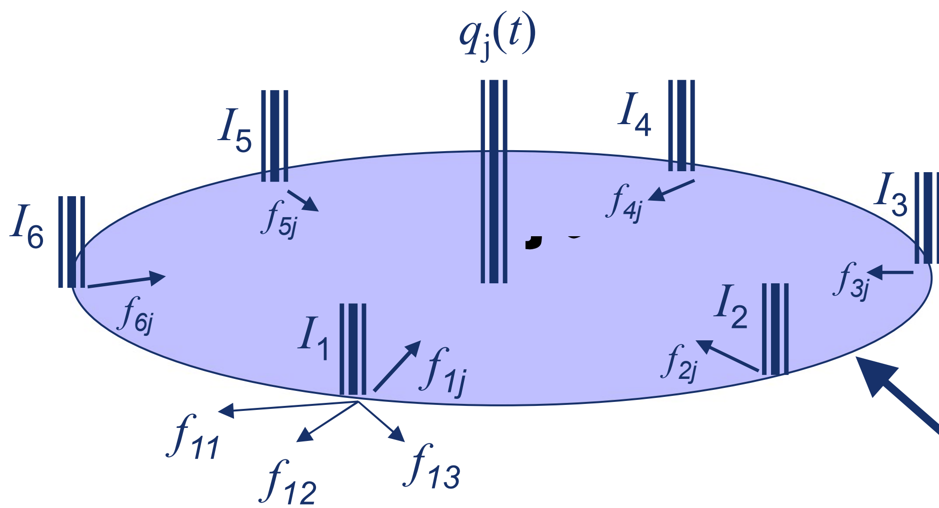
f_{ij} = 65%



Capacitance-Resistance Model (CRMP)

$$\tau_j = \left(\frac{c_t V_p}{J}\right)_j$$

Time constant



Drainage volume around a producer

$$\sum_{j=1}^{n_p} f_{ij} \le 1$$

Inter-well connectivity or gain

$$q_{jk} = q_{j(k-1)} e^{-\Delta t/\tau_j} + \left(1 - e^{-\Delta t/\tau_j}\right) \sum_{i=1}^{n_i} f_{ij} I_{ik}$$

Comparisons.....

Conventional world

$$\frac{1}{\alpha}\frac{\partial P}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right)$$

$$\alpha = \frac{k}{\mu\phi c_t}$$

$$k\,,\phi \text{ world}$$

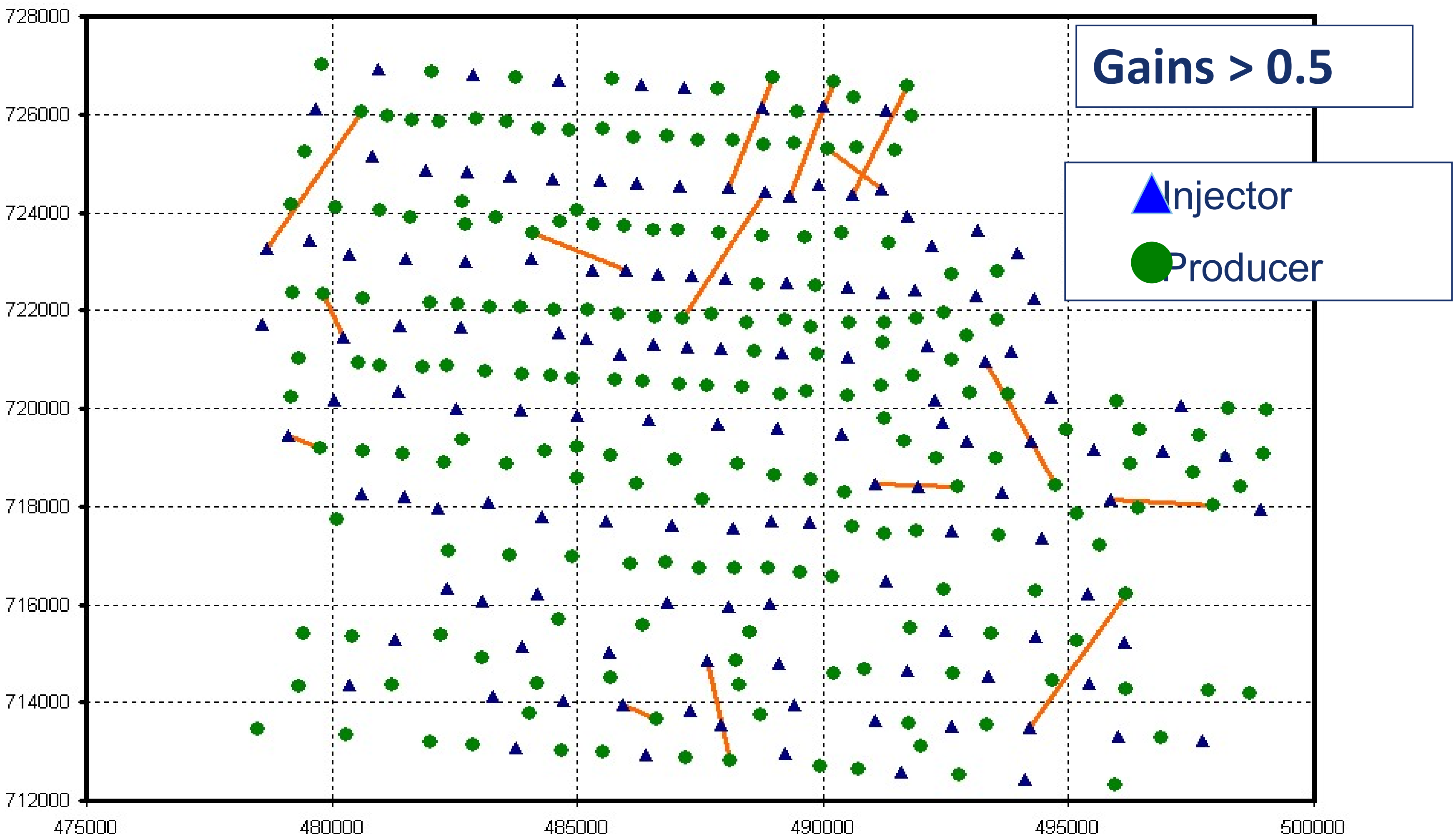
CRM world

$$c_t V_p \frac{d\bar{P}}{dt} = i(t) - q(t)$$

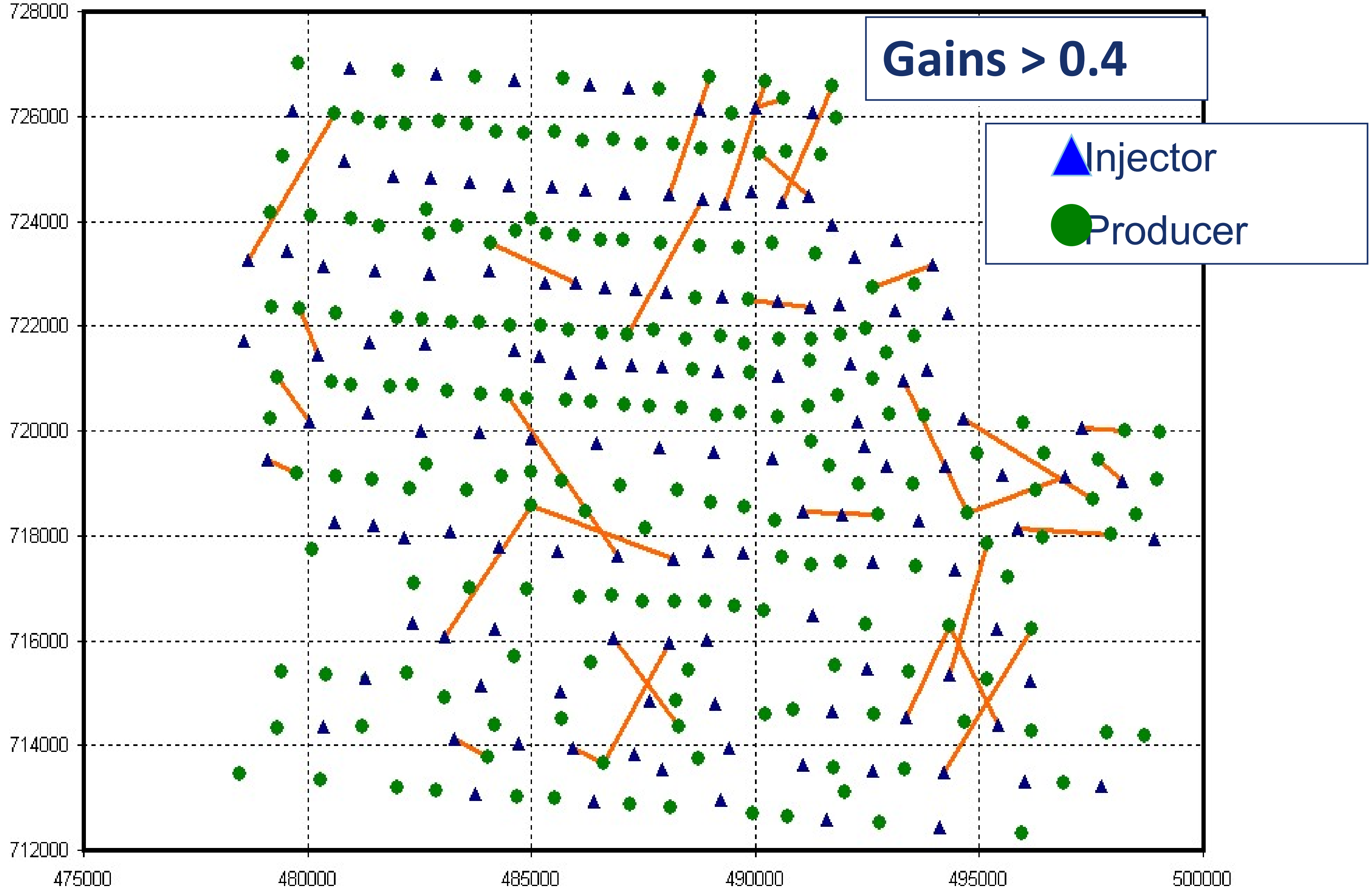
$$q = J\left(\bar{P} - P_{wf}\right)$$

$$\tau, V_p \text{ world}$$

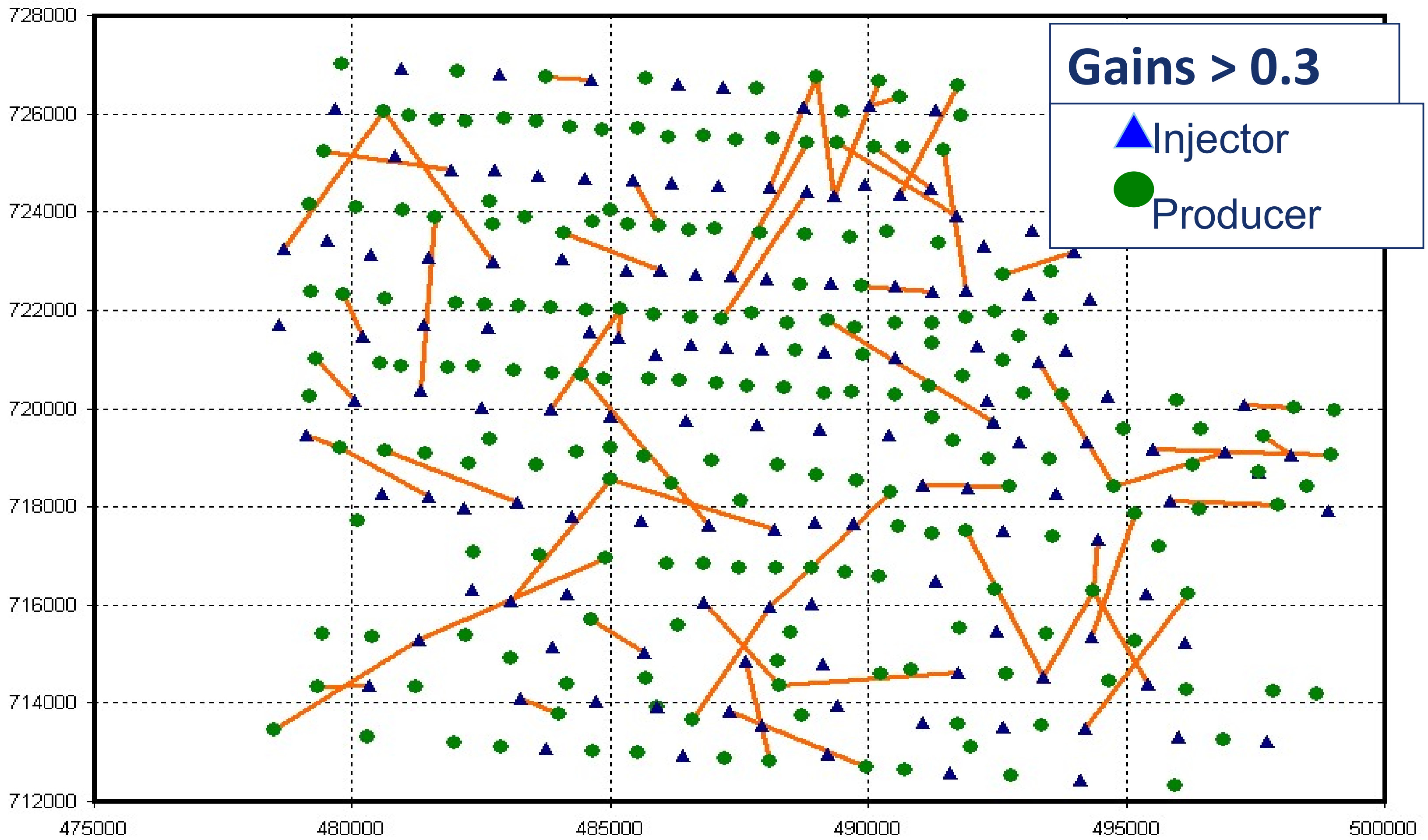
Mature West Texas Waterflood



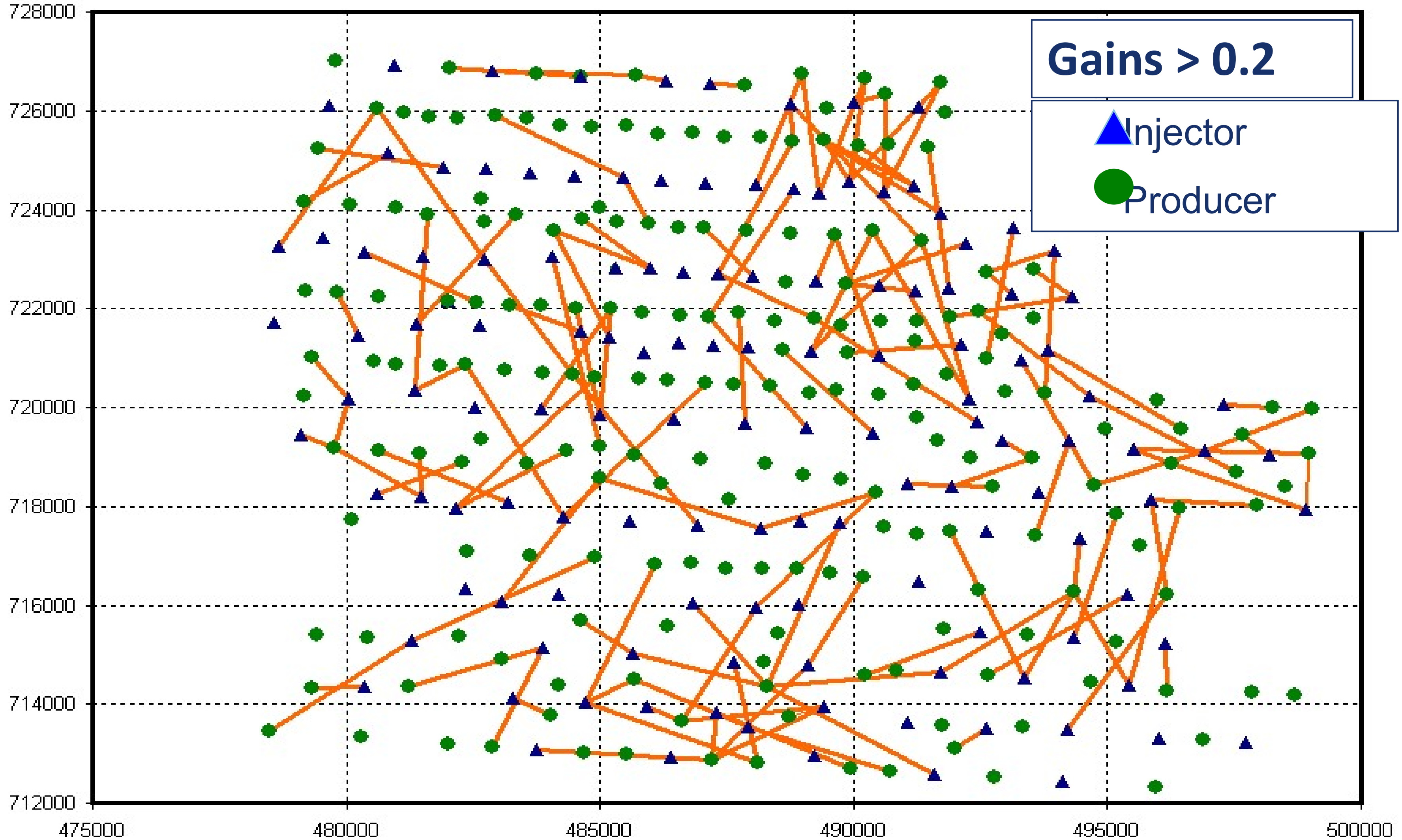
Mature West Texas Waterflood



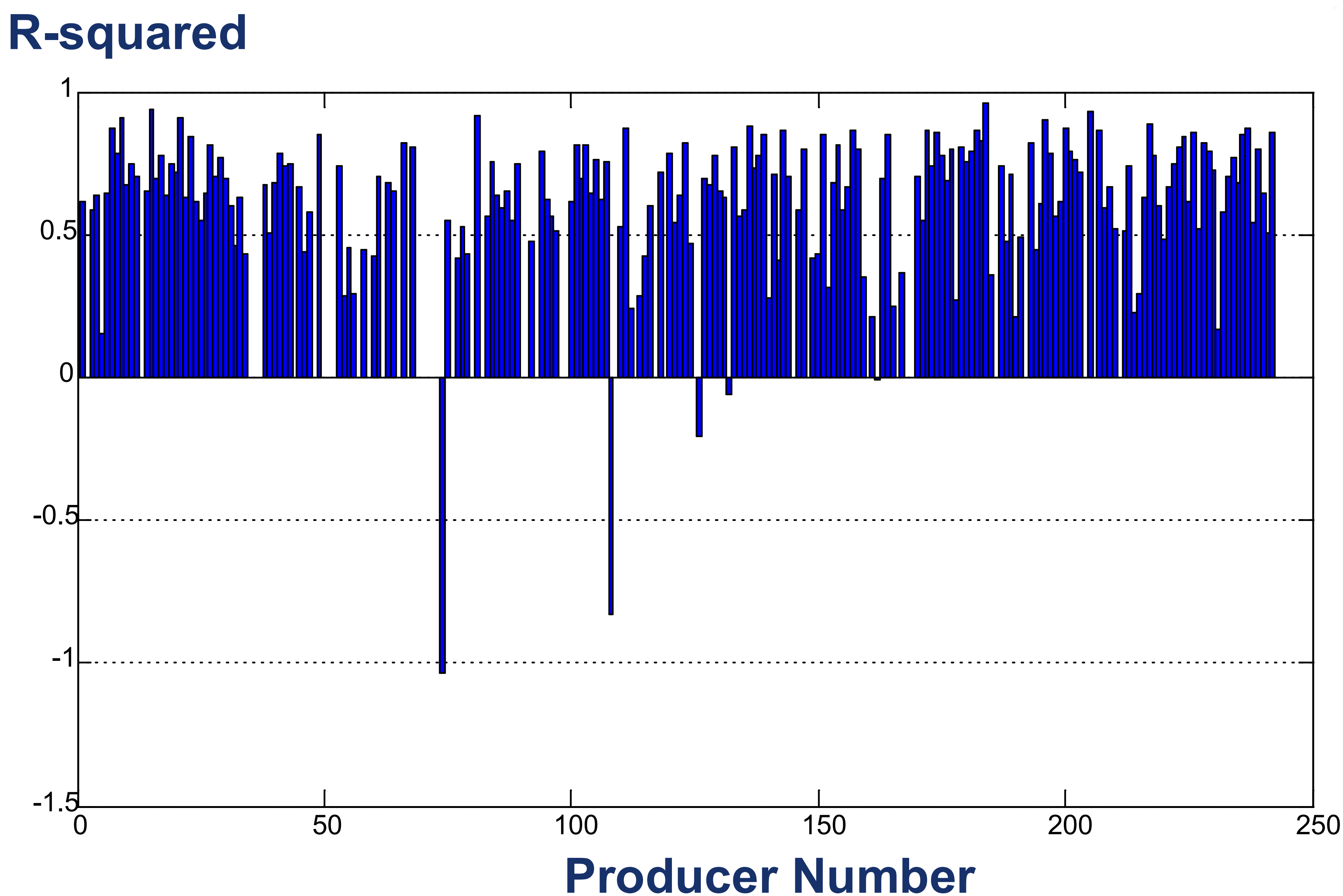
Mature West Texas Waterflood



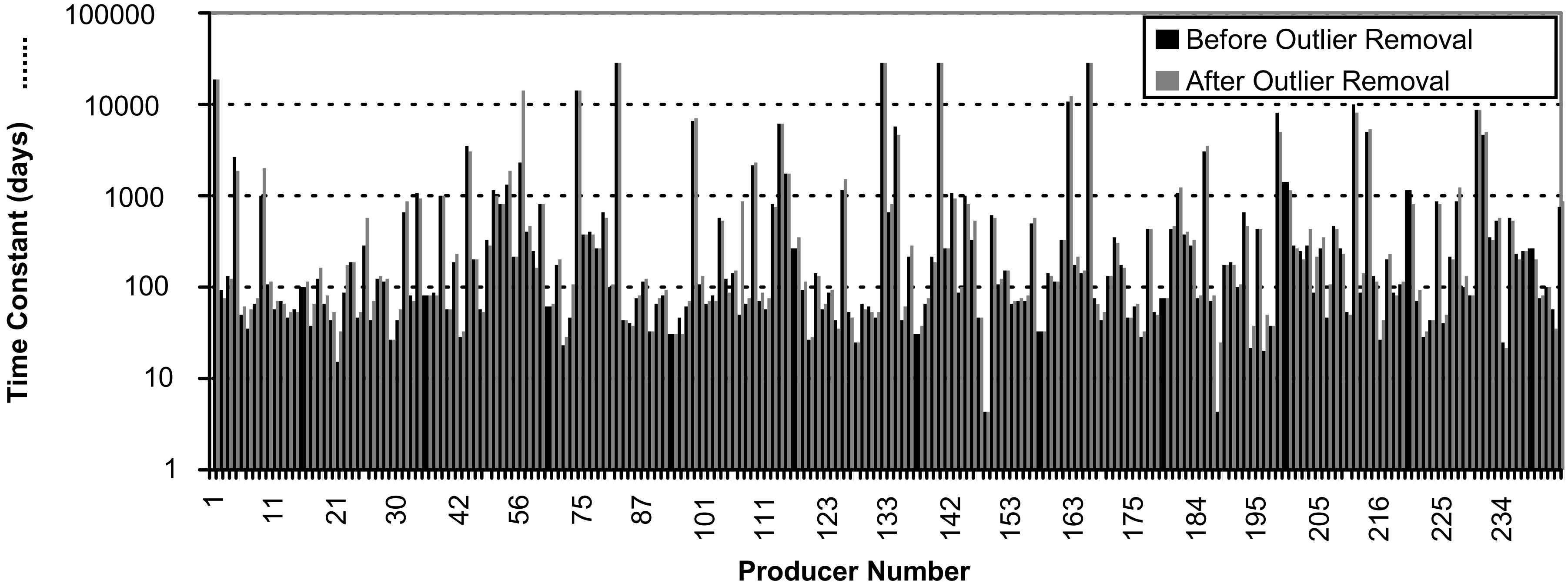
Mature West Texas Waterflood



Mature West Texas Waterflood

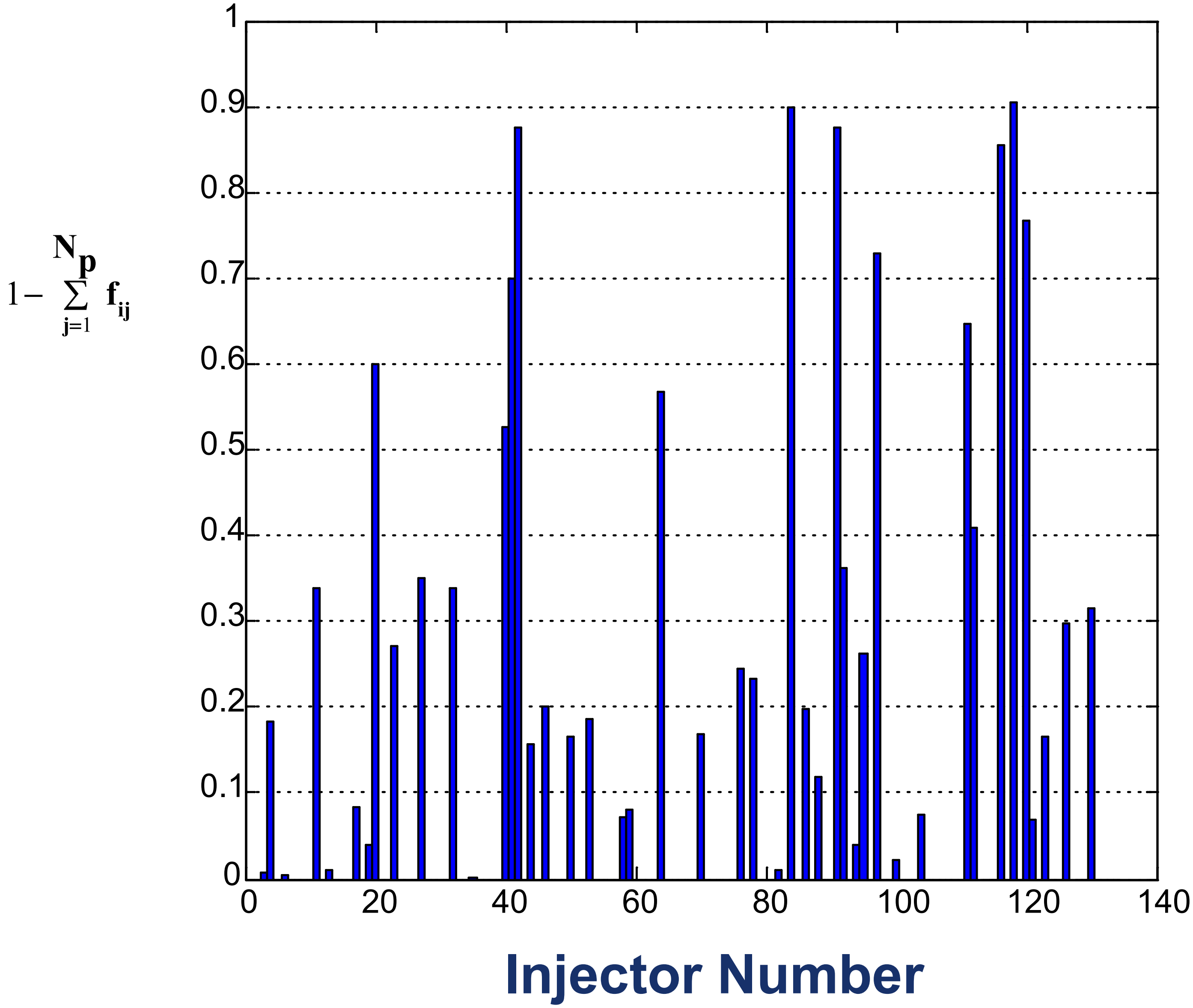


Time Constants



Reservoir A

Lost Injection



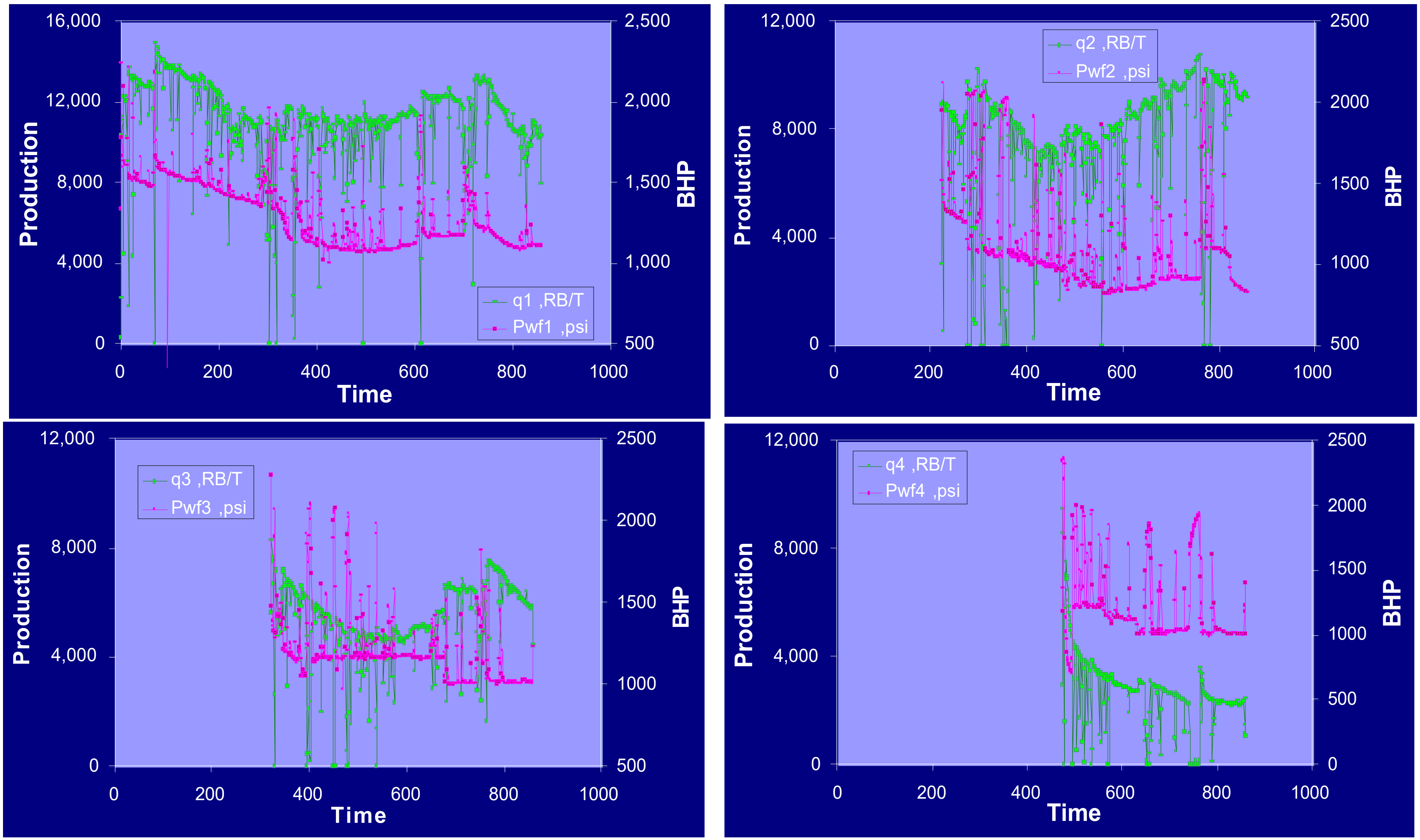
Basic Equations

- Applications
  - Effect of BHP
  - Primary production
  - CRM and tracers
  - Oil rate modeling
  - Optimization
  - Tracking CO2 floods
  - CRM machine learning

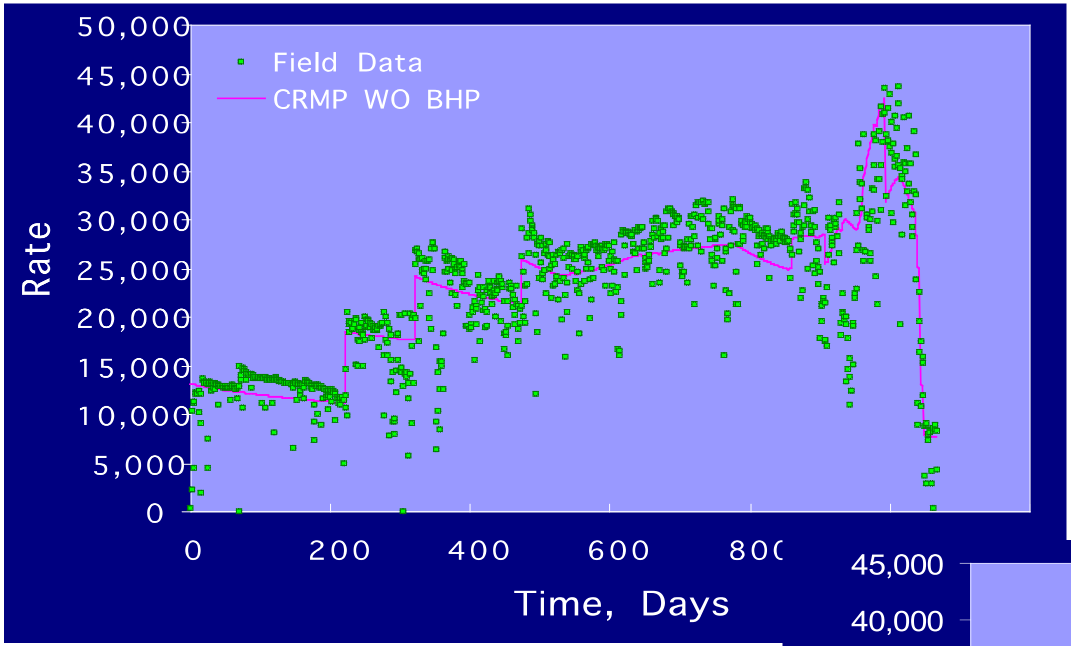
Basic Equations

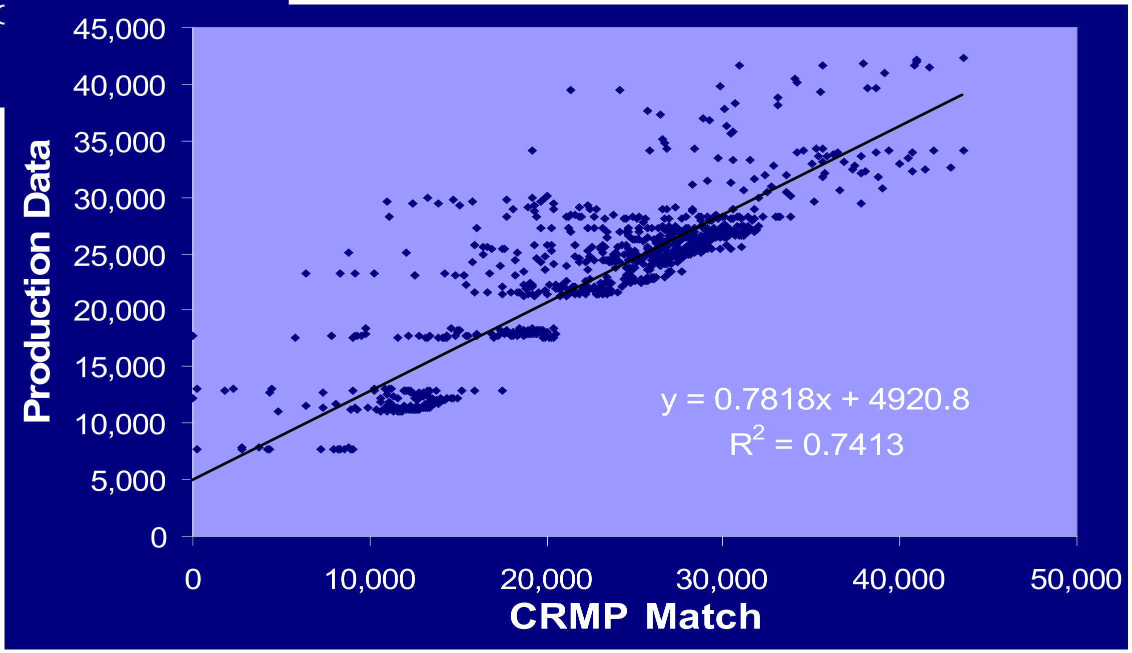
- Applications
  - Effect of BHP

North Sea Case
Production and BHP Data

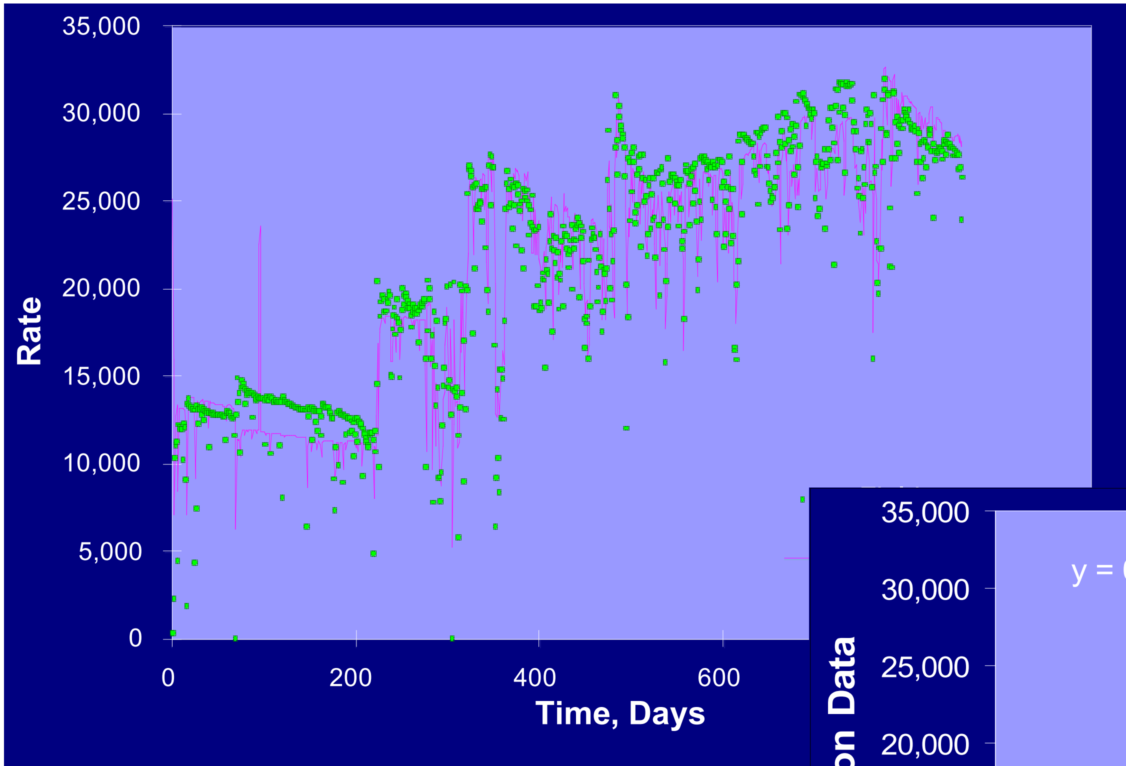


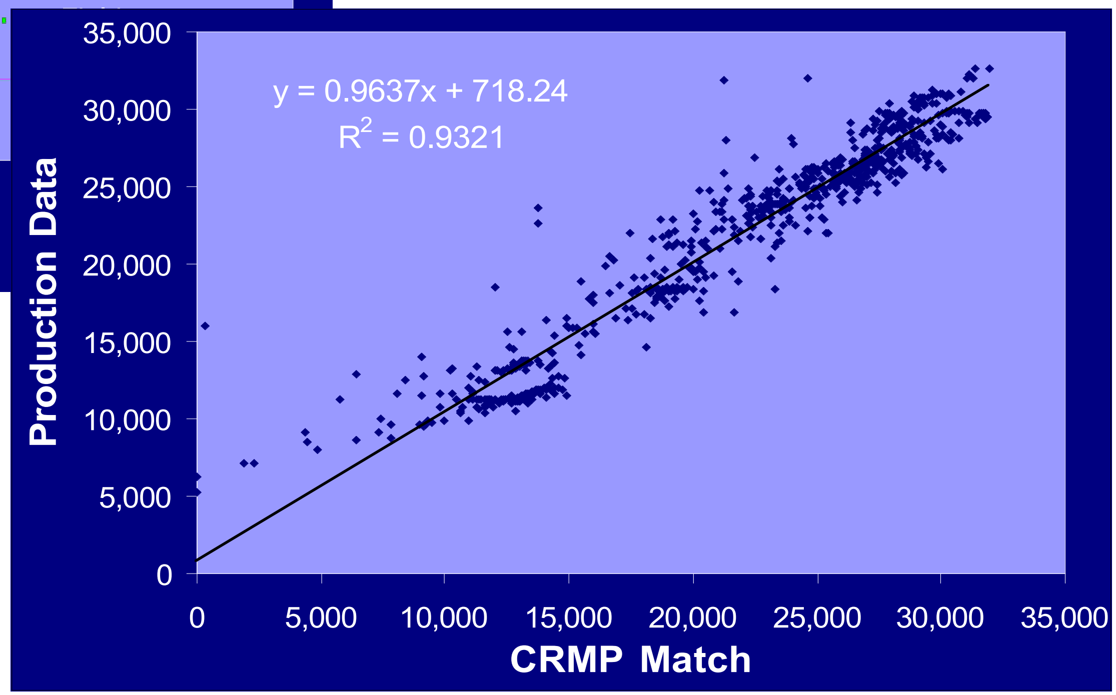
North Sea CRMP wo BHP



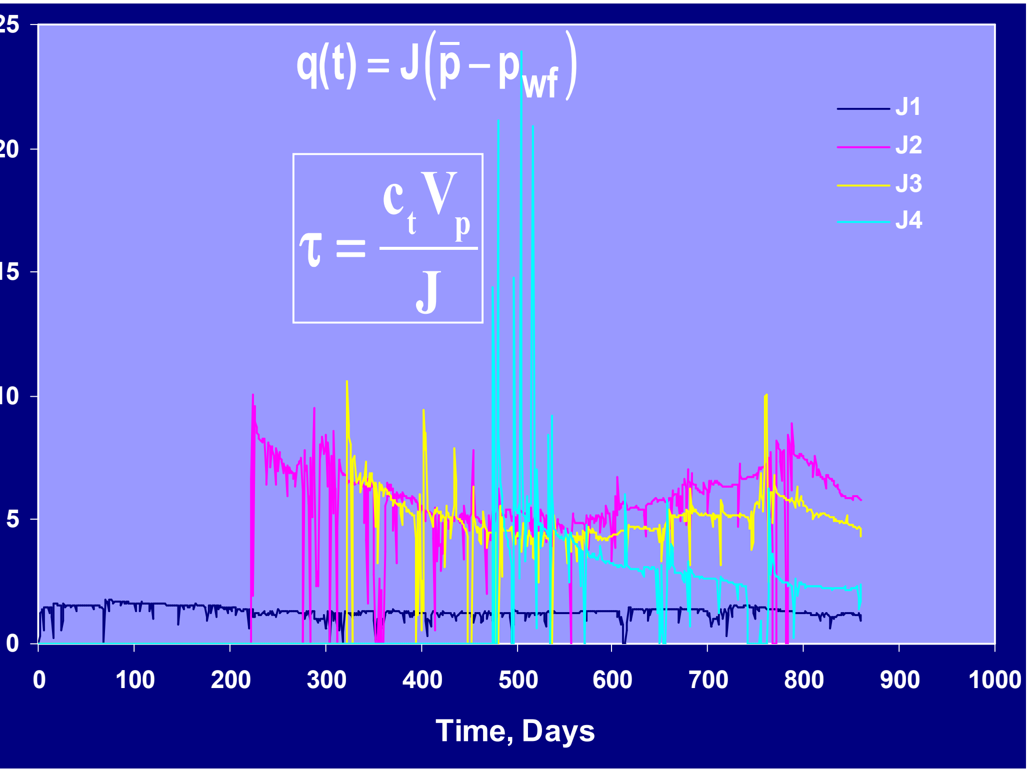


North Sea CRMP with BHP





Well Management--Identify Problem Wells



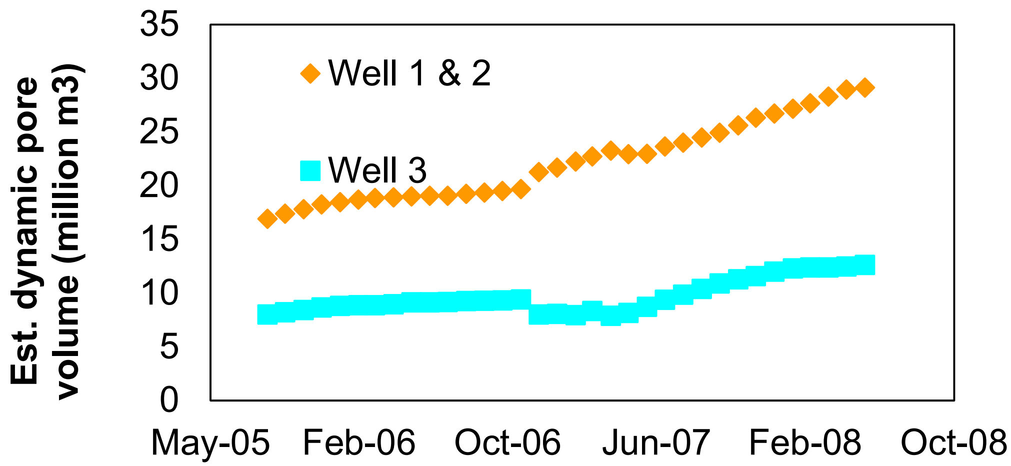
"Pressure is a reservoir engineer's best friend"
Fokert Brons

- Use productivity indices to evaluate well performance
- Requires pressure data

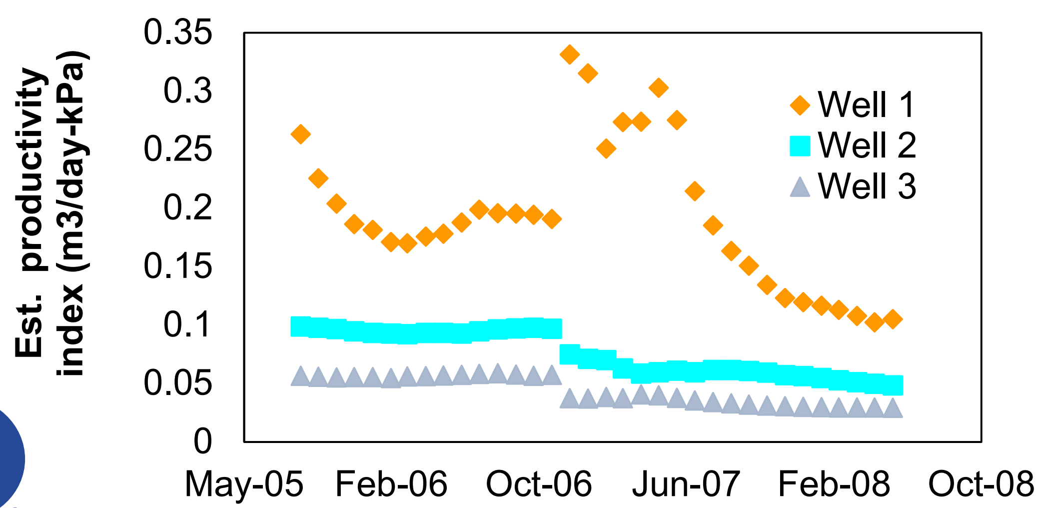
Basic Equations

- Applications
  - Effect of BHP
  - Primary production

Drainage Volume--Omani Field (primary recovery)



Original oil in place (OOIP) estimated from other methods ranged from 31 to 59 million m^3



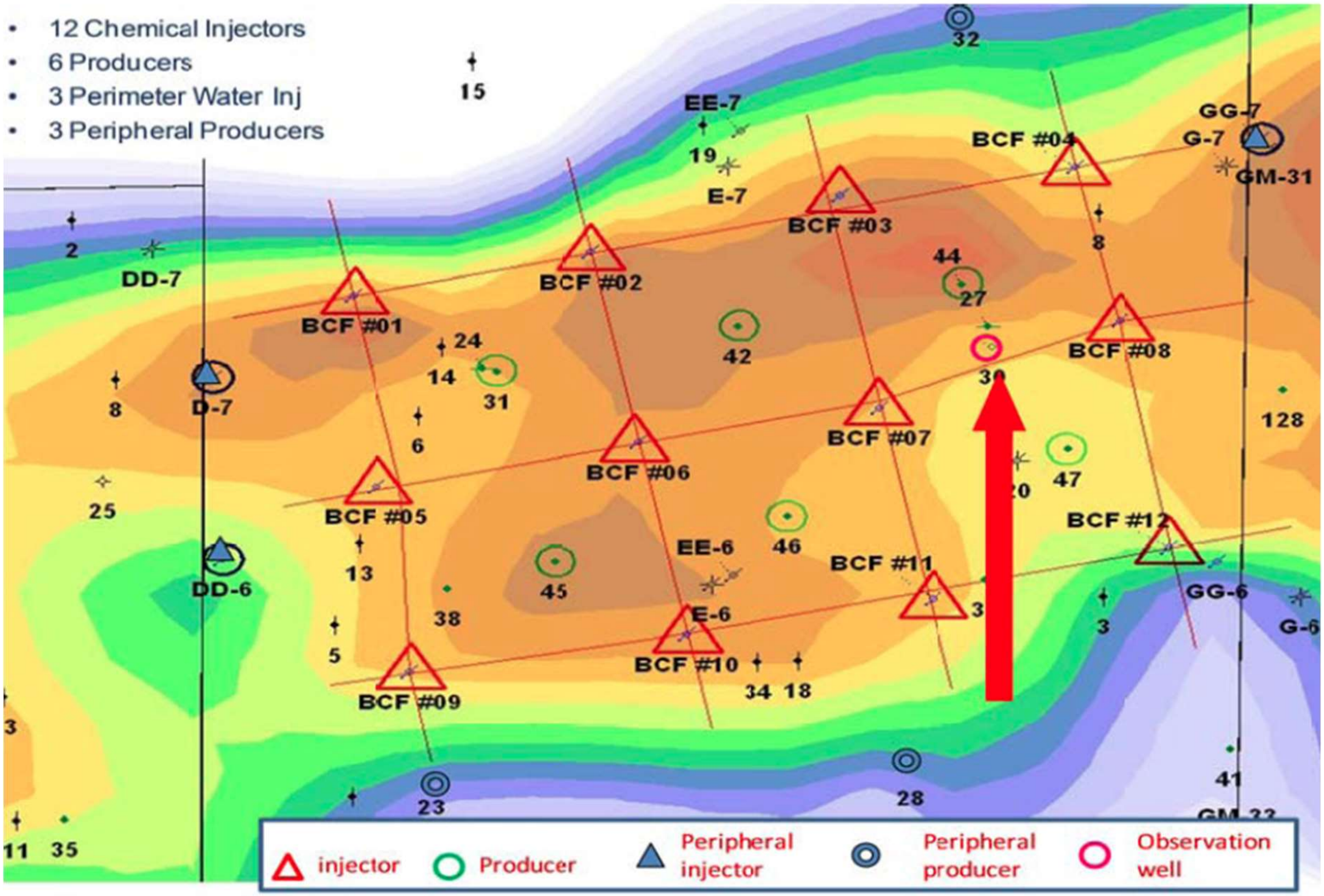
	Well 1	**Well 2**	**Well 3**
$V_p c_t$ (m^3/kPa)	76.75	74.66	3.25
V_p (10^6 m^3)	15.7	13.4	12.6
J (m^3/day kPa)	0.09	0.05	0.03
R^2	0.97	0.85	0.91

Basic Equations

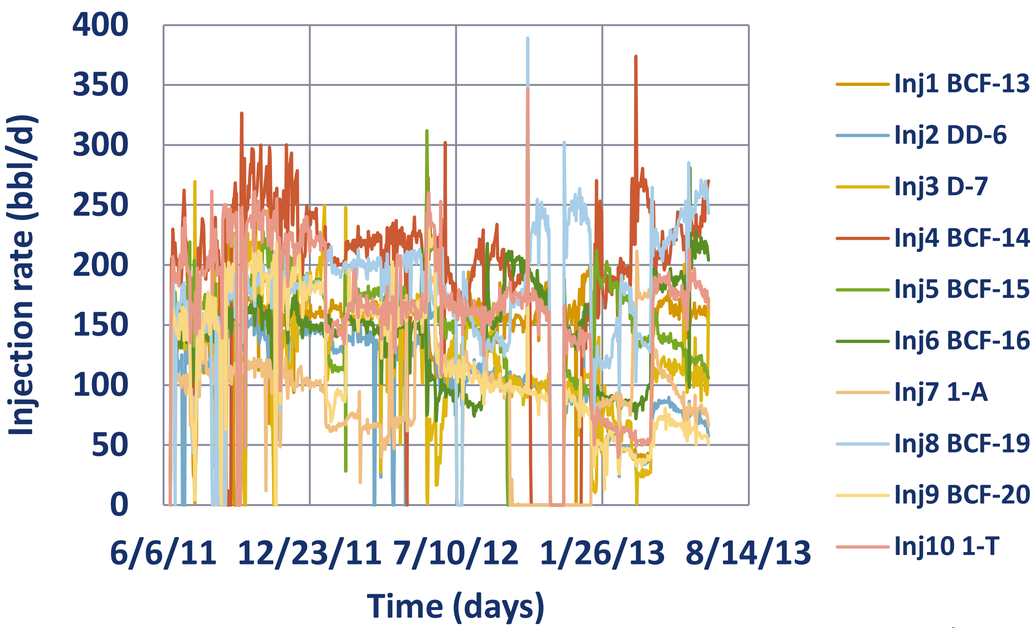
- Applications
  - Effect of BHP
  - Primary production
  - CRM and tracers

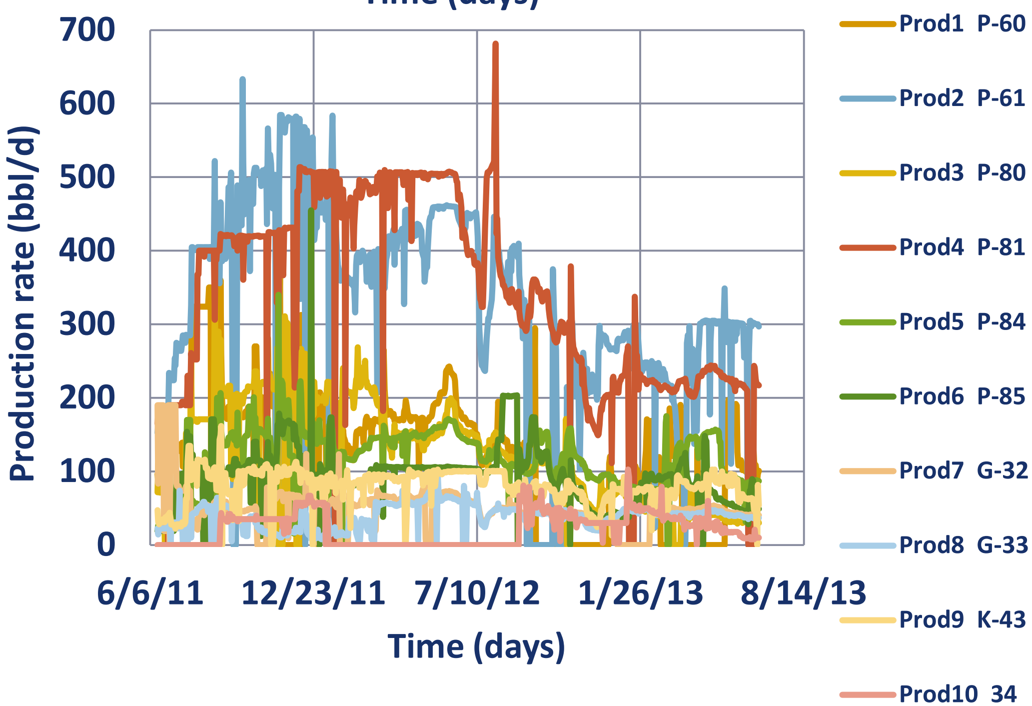
Reservoir Characterization

An alternative to tracers…

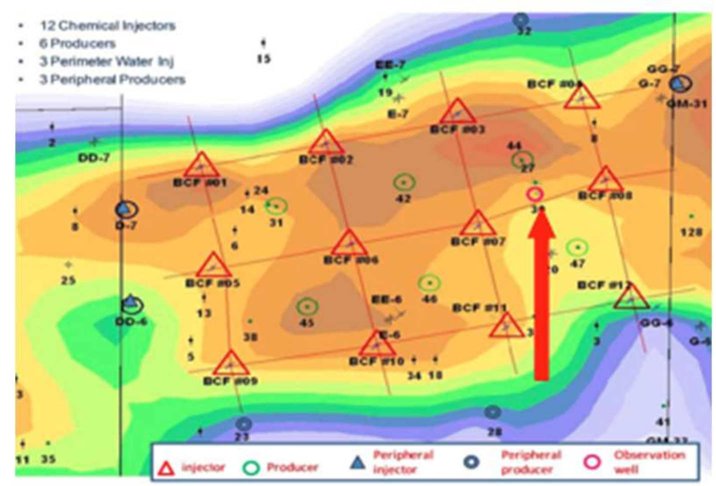


Variable Rates





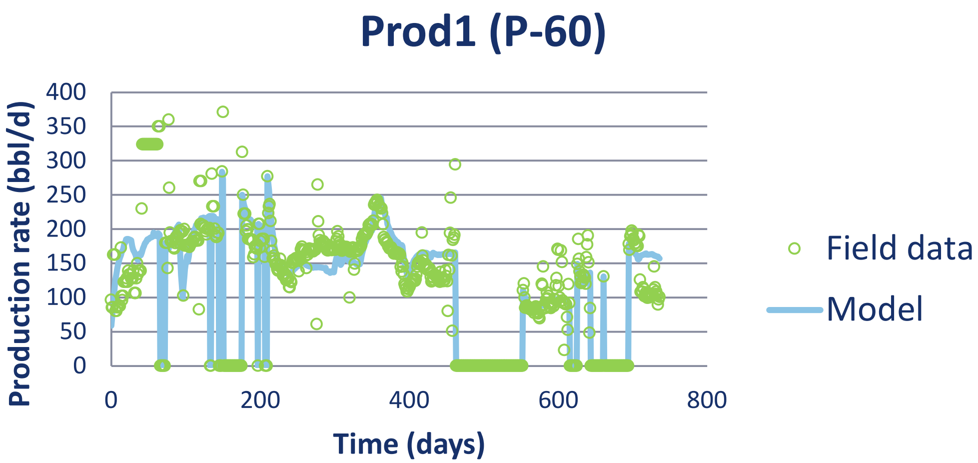
Injection

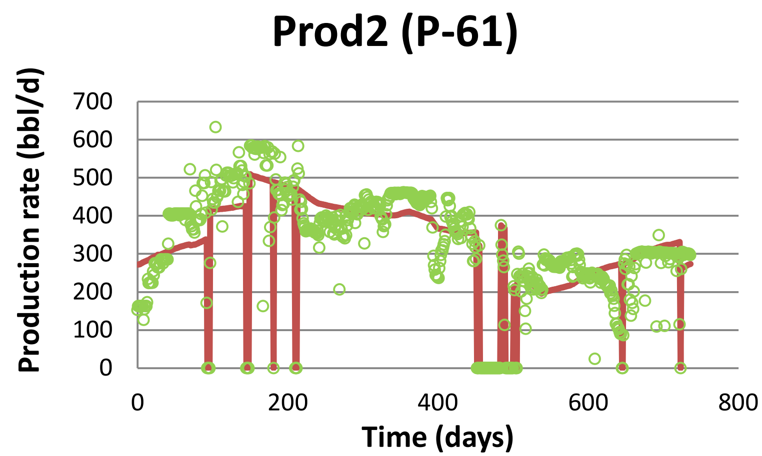


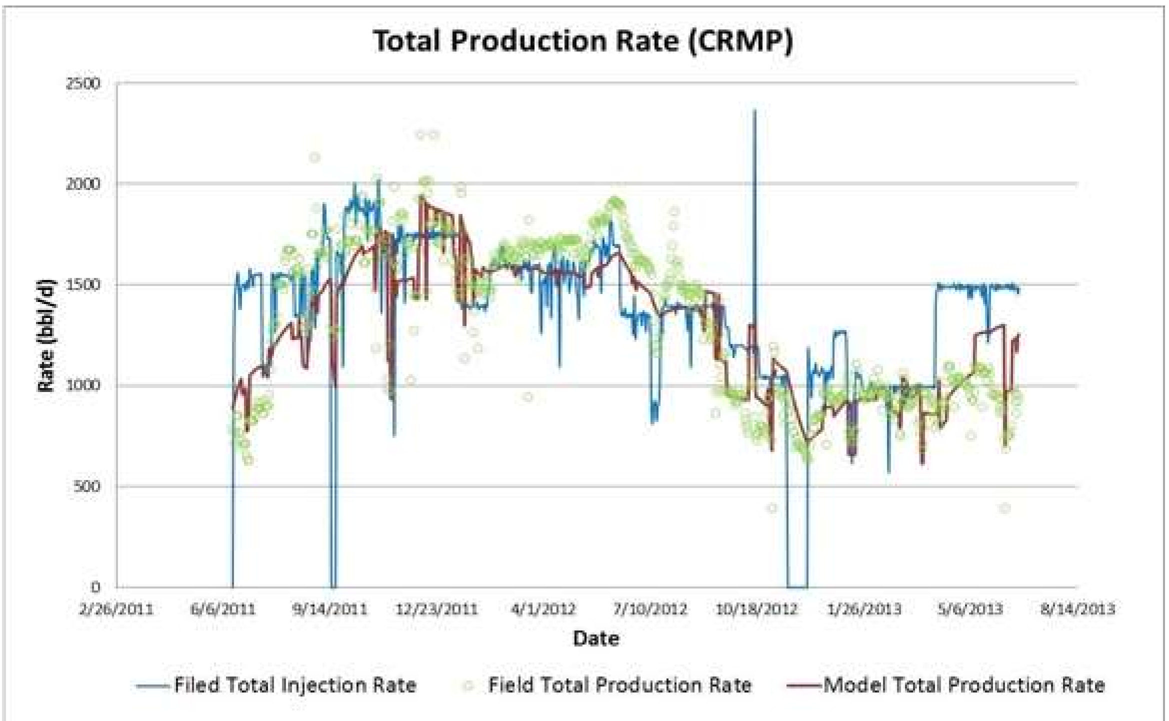
Production

CRM Production History Match

Individual Well and Full Field Matches

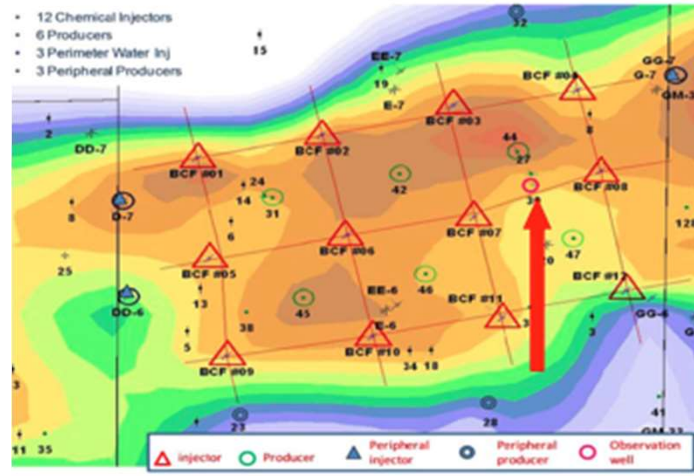






Tracer Performance—

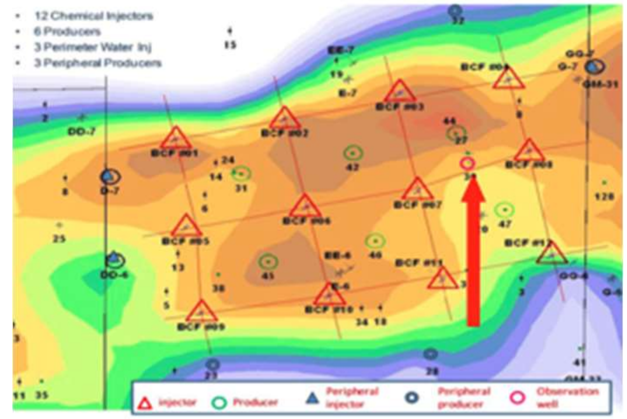
How does CRM compare?



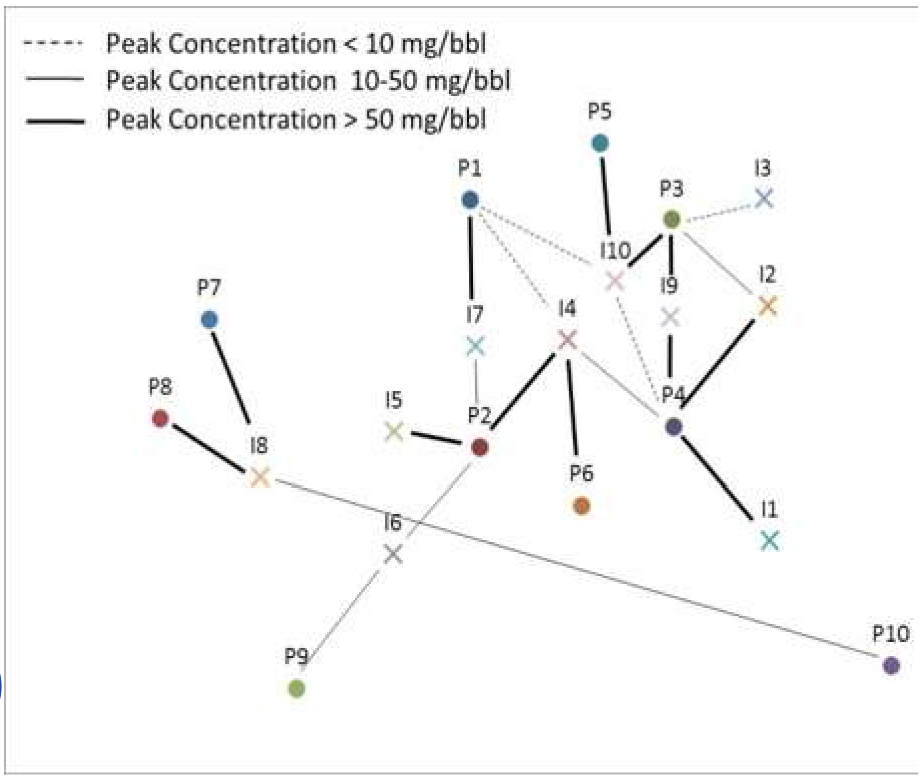
Injector	Tracer	Total injection (gr)	Field data			CRMP + Integrated Model (Simultaneous fitting)	
			Observed in Producer	Total measured produced tracer (gr)	Tracer recovery	Total produced tracer (gr)	Tracer recovery
Inj1	3,4,5-TFBA	6000	P4	3533	**59%**	3459	**58%**
Inj2	4-TFMBA	11000	P3, P4	6171	**56%**	7209	**66%**
Inj3	3,5-bisTFMBA	7500	P3	115	**2%**	0	**0%**
Inj4	2,3,4,5-TFBA	17000	P1,P2,P4,P6	9551	**56%**	7881	**46%**
Inj5	2,4,5-TFBA	7500	P2	6472	**86%**	6517	**87%**
Inj6	2,4-DFBA 4-FBA	7500	P2,P9	3257	**43%**	3292	**44%**
Inj7	2-TFMBA	7500	P1,P2	3034	**40%**	3815	**51%**
Inj8	3-TFMBA 2-FBA	7500	P7,P8,P10	2547	**34%**	2279	**30%**
Inj9	2,3,4-TFBA	10000	P3, P4	11479	**115%**	11714	**117%**
Inj10	2,5-DFBA	7500	P1,P3,P4,P5	4547	**61%**	5027	**67%**

Tracer and CRM Results

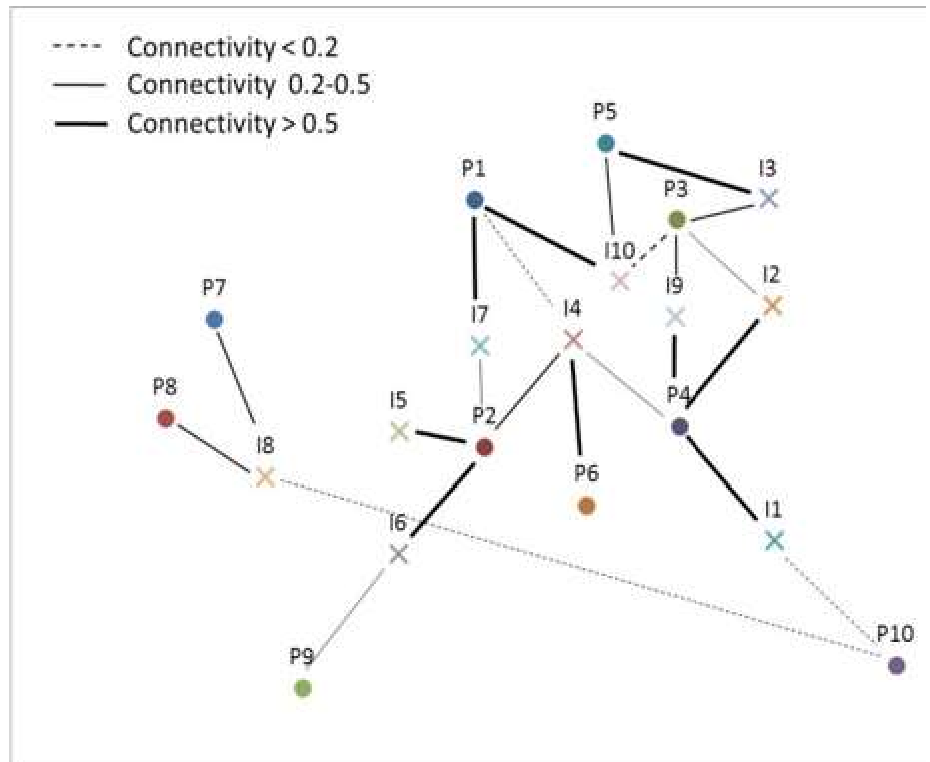
A side by side comparison…



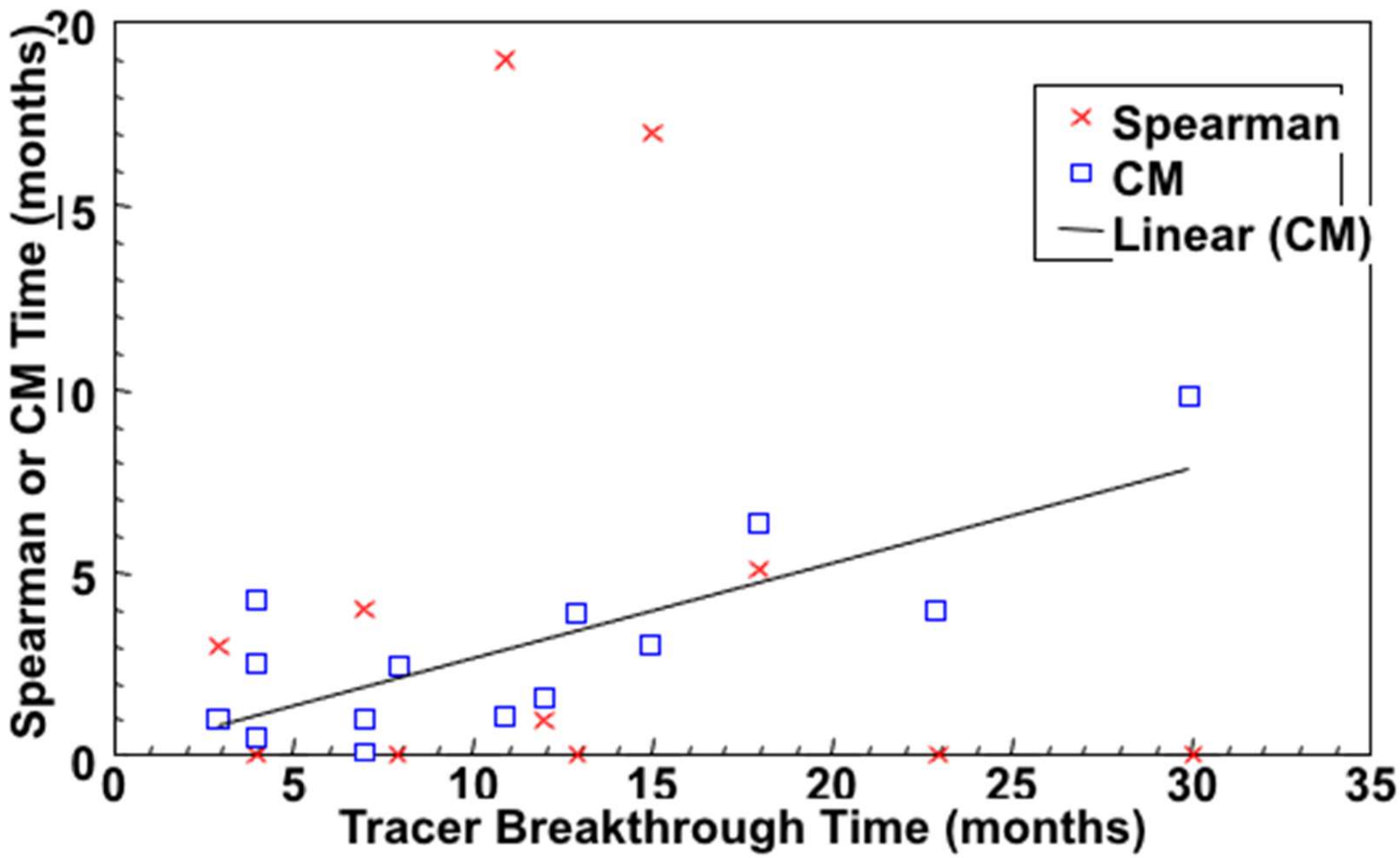
Tracer Peak Concentrations



CRM Allocations



Comparison to Buck Draw Data



Basic Equations

Applications

- Effect of BHP
- Primary production
- CRM and tracers
- Oil rate modeling

Oil Rate Equation

$$\mathbf{q_{oil}(t) = q(t)\,f_{oil}(t)}$$

For each well in CRMP

$$\mathbf{q_{oil}(t) = q(t)\left(1 - f_{water}(t)\right)}$$

	Developed by	Oil Fractional-flow Model	Equation Number
1	Timmermann (1971)	$f_o = \left(1+10^{\square(a+bN_p)}\right)^{\square 1}$	Eq. (4-7)
2	Makszimov (1959)	$f_o = \left(1+ba^{N_p}\ln a\right)^{\square 1}$	Eq. (4-8)
3	Craft-Hawkins (1959); Ershagi-Omoregie (1978)	$f_o = \left(1+ae^{bS_w}\right)^{\square 1}$	Eq. (4-9)
4	Kazakov (1976)	$f_o = \dfrac{(1\square bN_p)^2}{(a\square 2bN_p)(1\square bN_p)+bN_p(a\square bN_p)}$	Eq. (4-10)
5	Gunkel Marsal-Philip (1968)	$f_o = \left(1+a+(1+cN_p)be^{cN_p}\right)$	Eq. (4-11)
6	Gentil (2005)	$f_o(t) = \dfrac{1}{1+F_{wo}} = \dfrac{1}{1+\square W_i^{\square}}$	Eq. (4-12)

CRM: Oil Fractional-Flow Model

$$q_o(t) = q(t) f_o(t)$$

$$f_o(t) = \frac{q_o(t)}{q_o(t) + q_w(t)} = \frac{1}{1 + WOR(t)}$$

$$f_o(t) = \frac{1}{1 + a\left(CWI(t)\right)^b}$$

$$\log\left(\frac{1}{f_o(t)} - 1\right) = \log a + b \log CWI(t)$$

A Method for Predicting the Performance of Unstable Miscible Displacement in Heterogeneous Media

E. J. KOVAL*
CALIFORNIA RESEARCH CORP.
LA HABRA, CALIF.

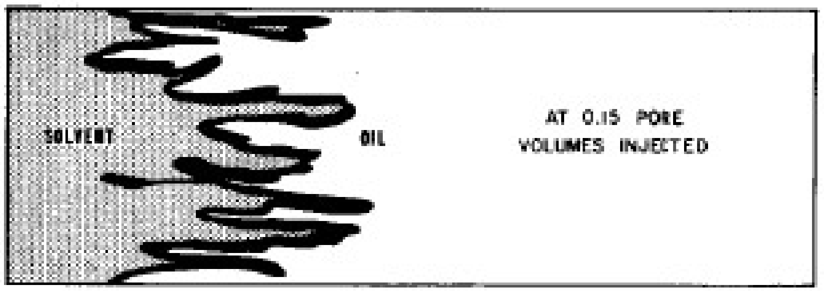
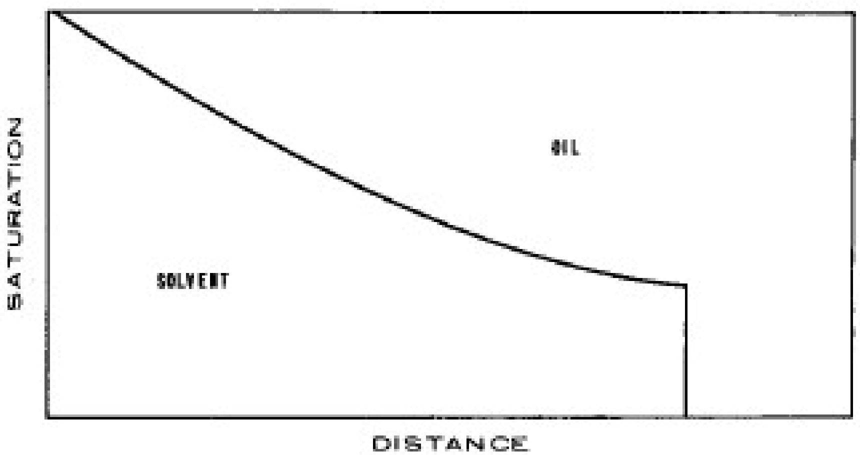
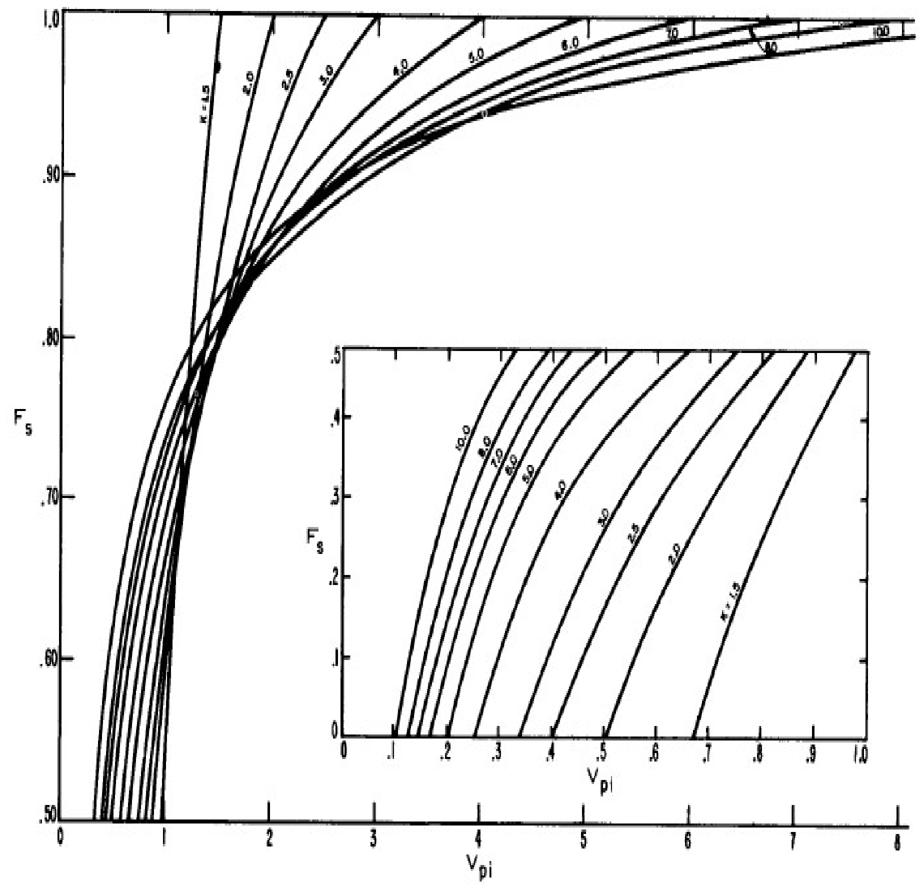


FIG. 4 — OBSERVED DISPLACEMENT FRONT FOR VISCOSITY RATIO OF 20 (AFTER BLACKWELL[8]).





Koval Model

A Method for Predicting the Performance of Unstable Miscible Displacement in Heterogeneous Media

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CALIFORNIA RESEARCH CORP.
LA HABRA, CALIF.

Koval model:

$$f_1 = \frac{1}{1 + \frac{(1 - C_1)}{K_v C_1}}$$

$$K_v = H_k E$$

H_k Heterogeneity factor

E = effective viscosity ratio

$H_k = 1$ (homogeneous) $\quad E = 1$ (tracer)

Basic Equations

Applications

- Effect of BHP
- Primary production
- CRM and tracers
- Oil rate modeling
- Optimization

Waterflood and EOR Optimization Work Flow

Workflow for Optimization

Fit CRM to total production data

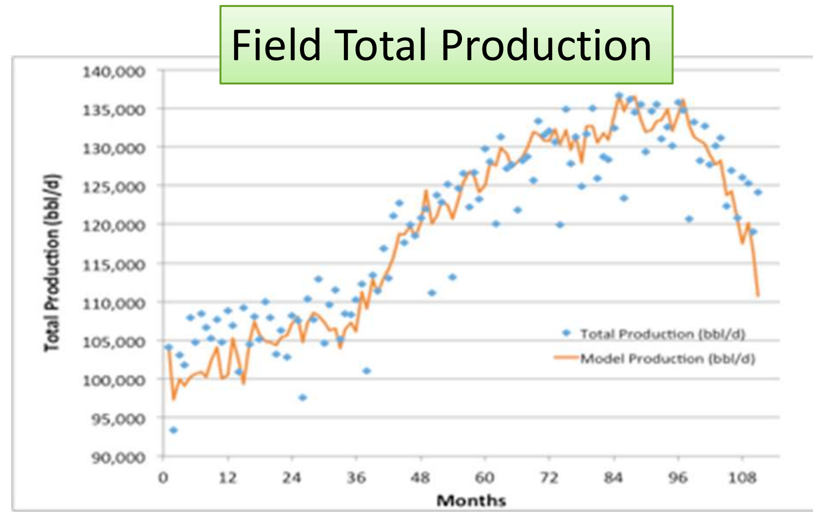
↓

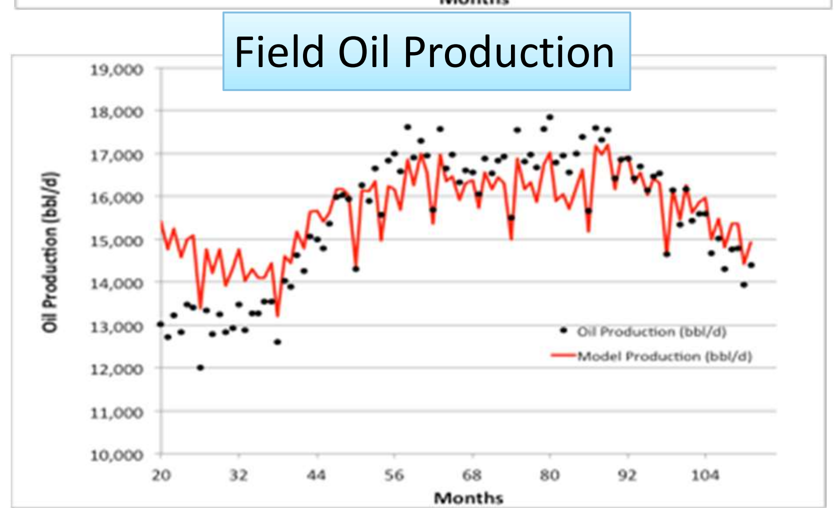
Fit oil fractional flow model to oil production

↓

Use CRM and oil fractional flow model to optimize future injection and maximize NPV of future production

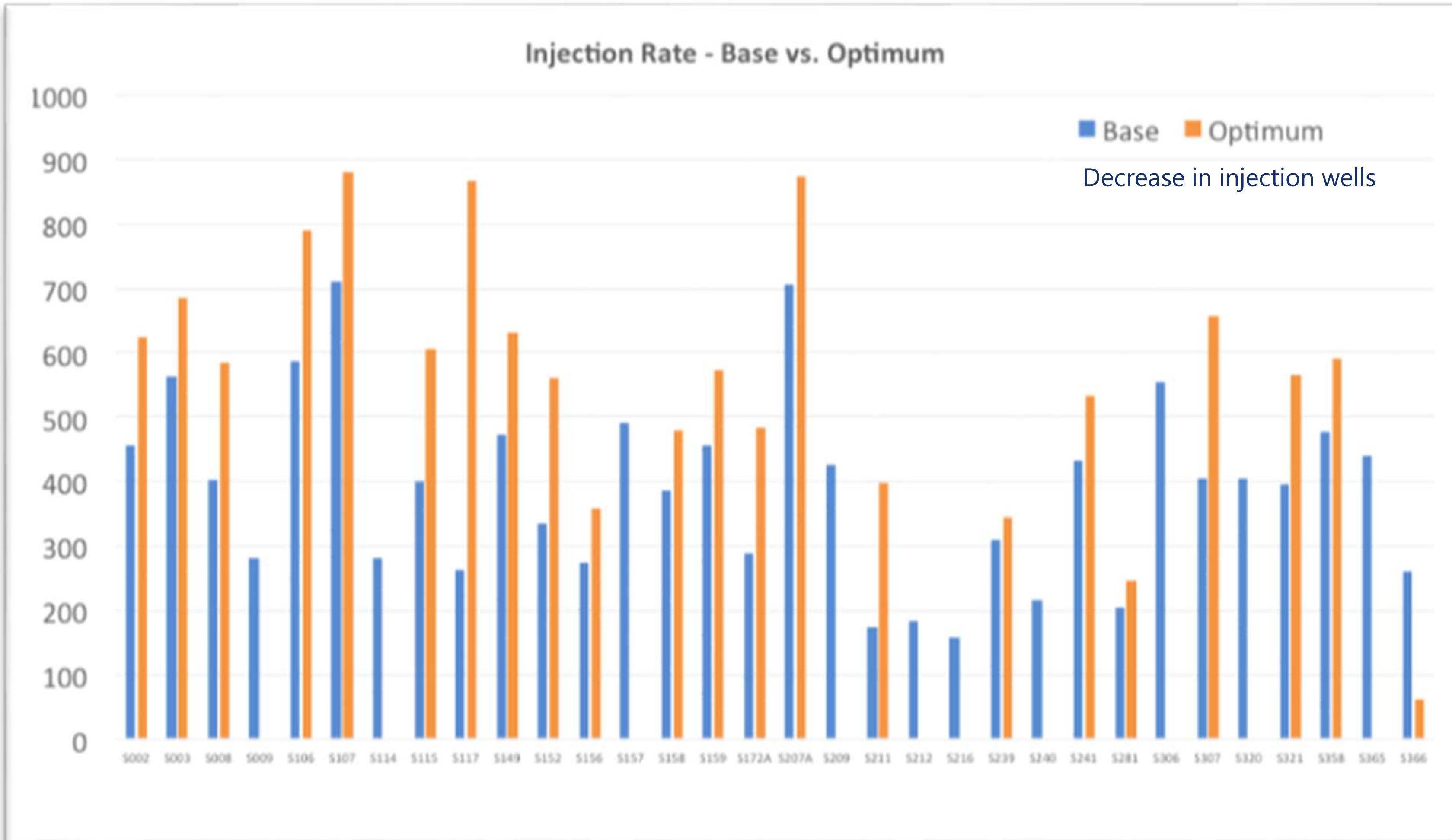
$$NPV = \sum_{j=1}^{n_p}\sum_{k=1}^{n_t} \frac{p_o q_{oj}(t_k; f_{ij}, \tau_j)}{\left(1+D_f\right)^k}\Delta t - \sum_{i=1}^{n_i}\sum_{k=1}^{n_t} \frac{p_w}{\left(1+D_f\right)^k} I_i(t_k)\Delta t$$



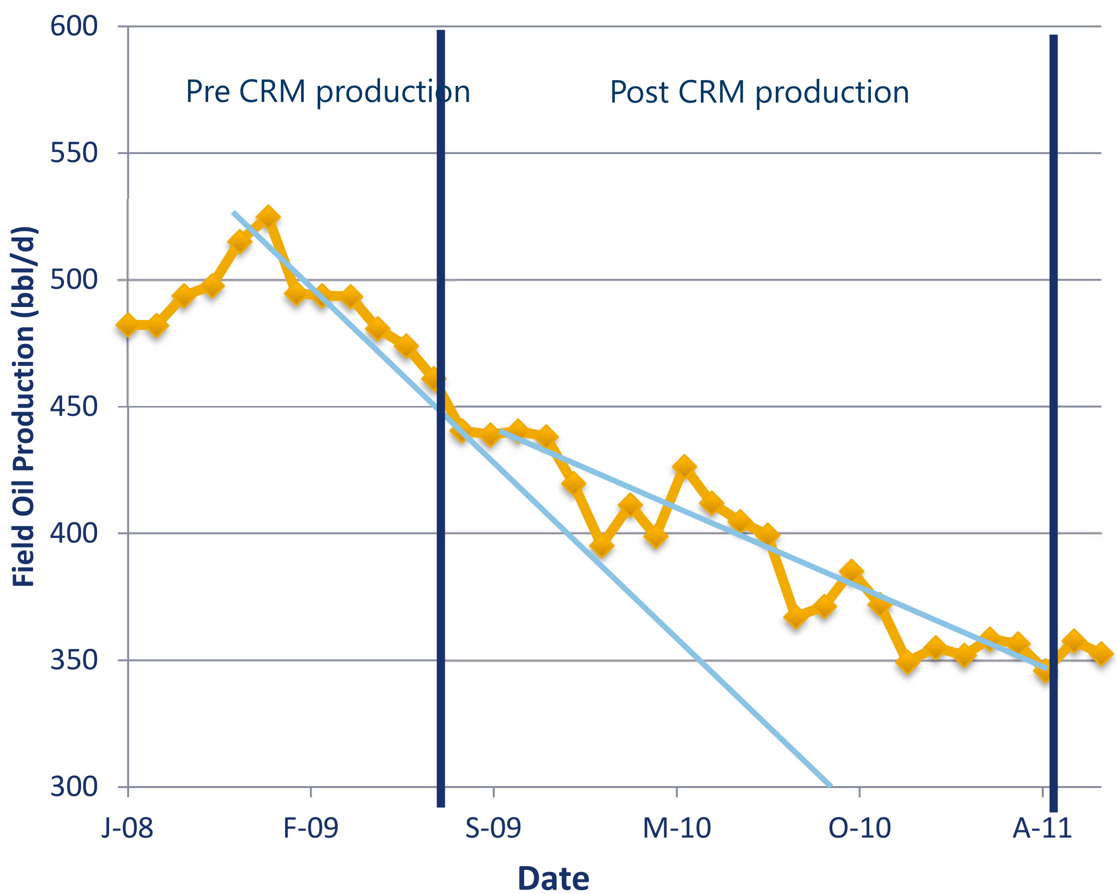


The Technology

CRM Optimizes Operations

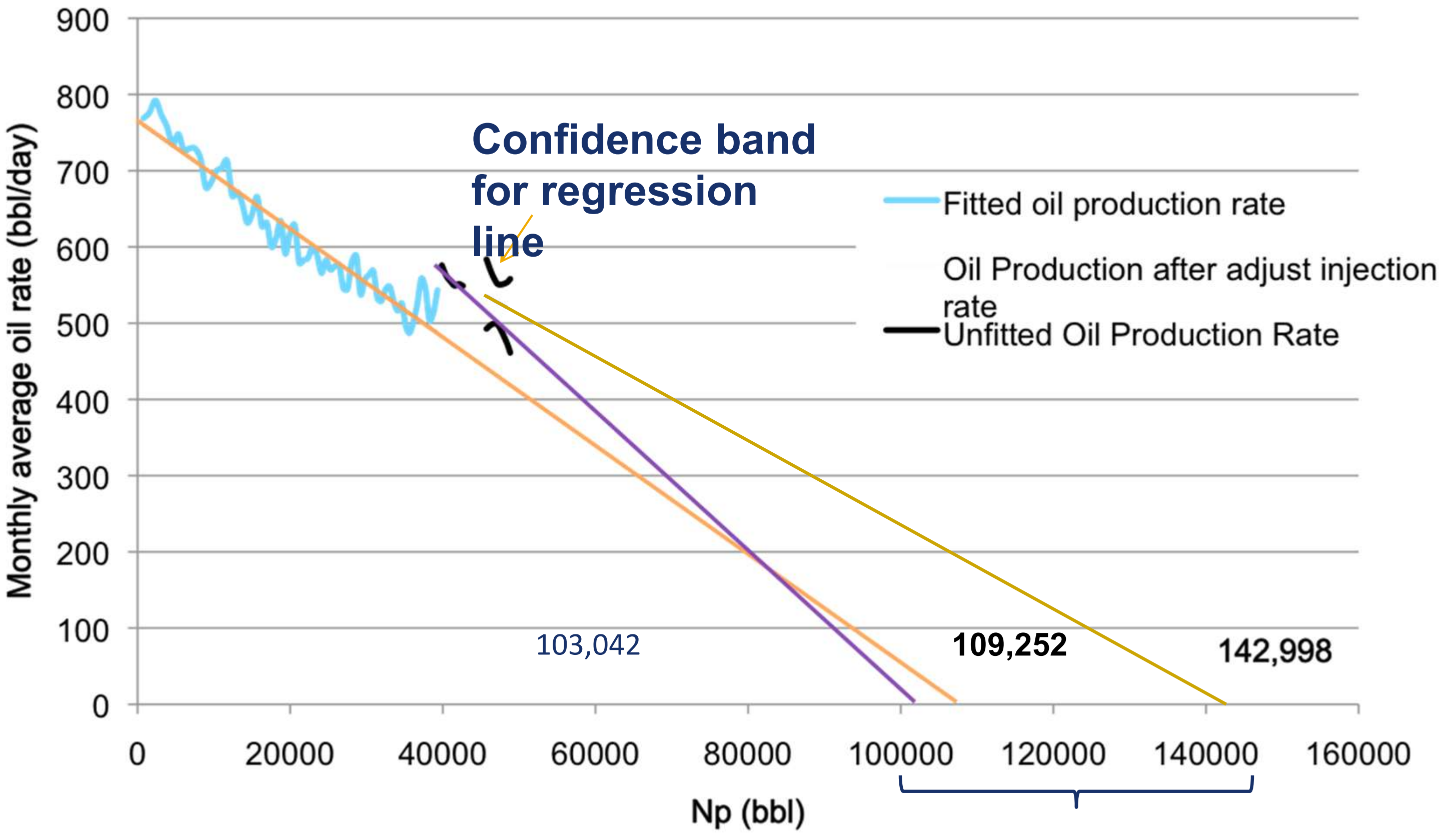


...he Technology
...RM Optimizes Production - Proof



- Permian Study (Nguyen et al., 2012)
- Optimized oil production
- Modified only injection
- Reduced decline
- No additional capital costs

Rate vs. Cumulative Oil Production Oil



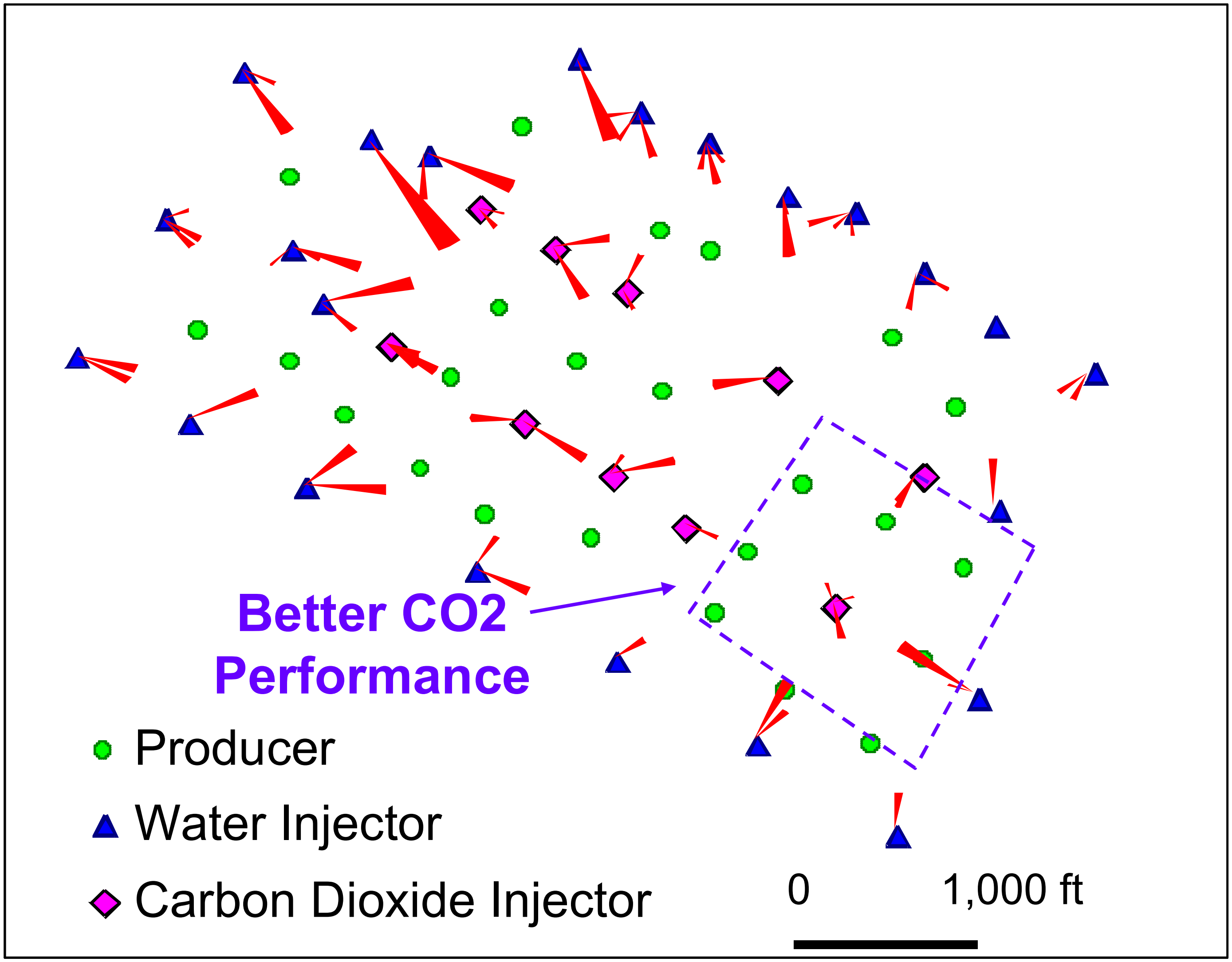
39,956 bbl
~ $2,800,000

Basic Equations

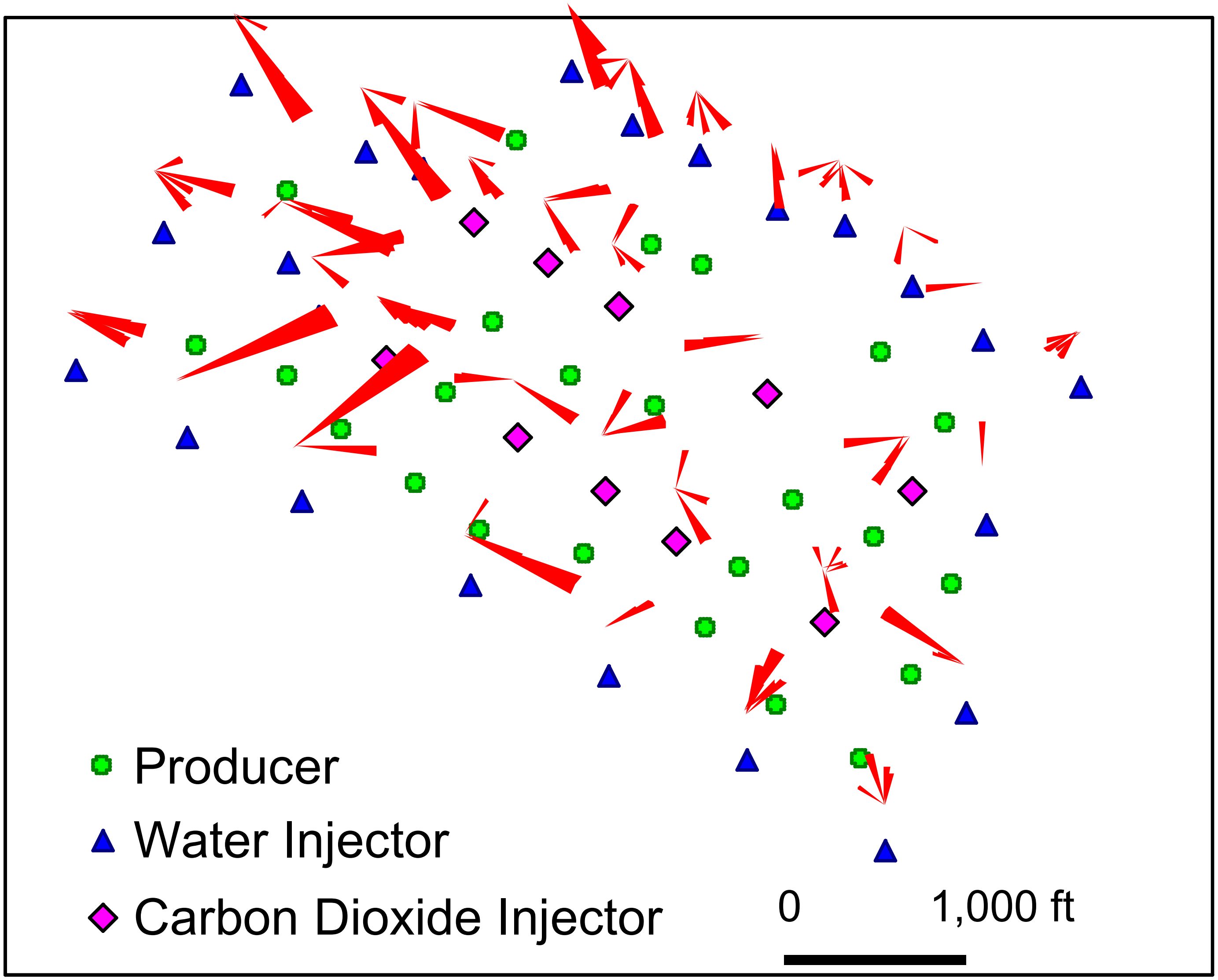
Applications

- Effect of BHP
- Primary production
- CRM and tracers
- Oil rate modeling
- Optimization
- Tracking CO_2 fronts

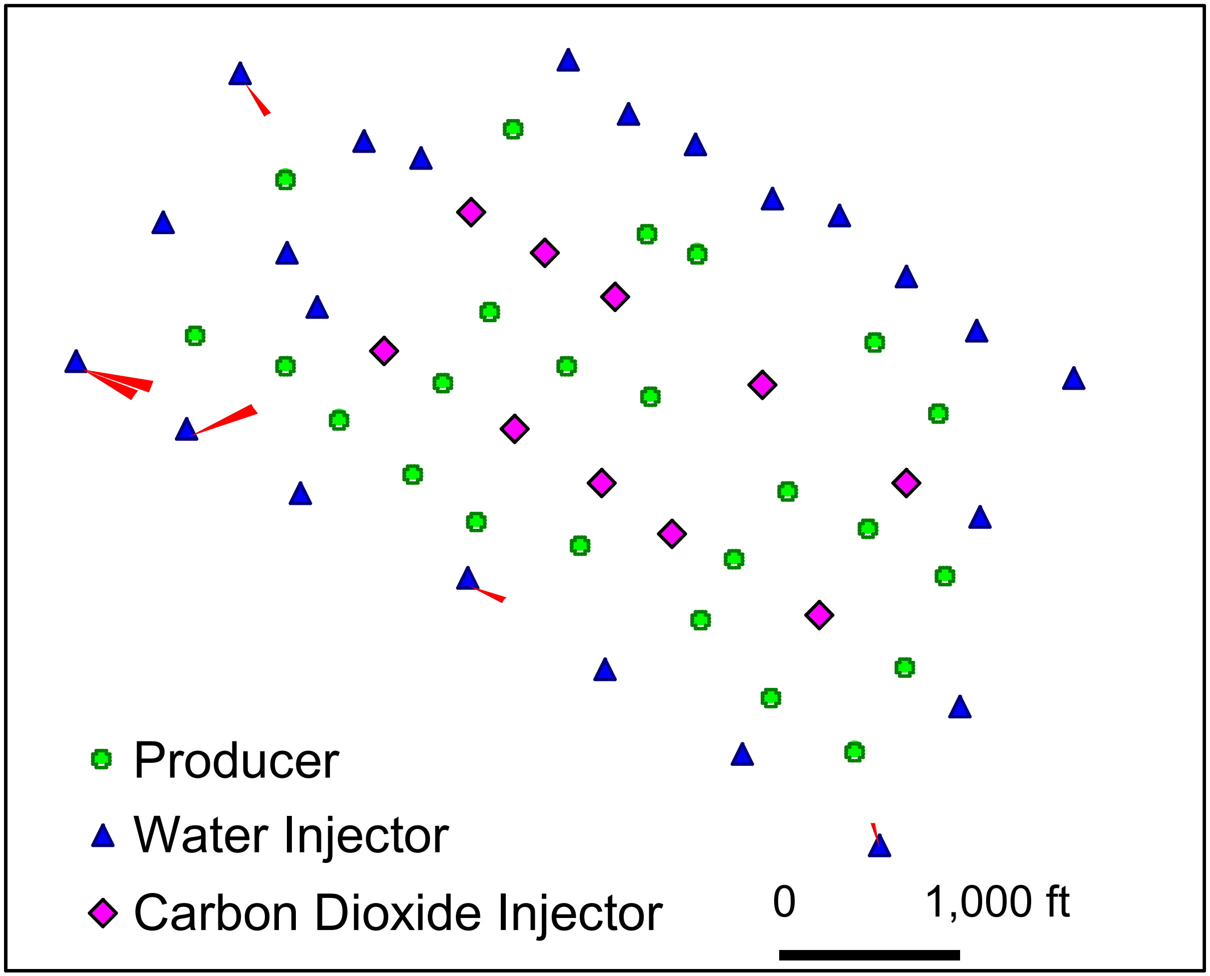
Steady-State Connectivity Map



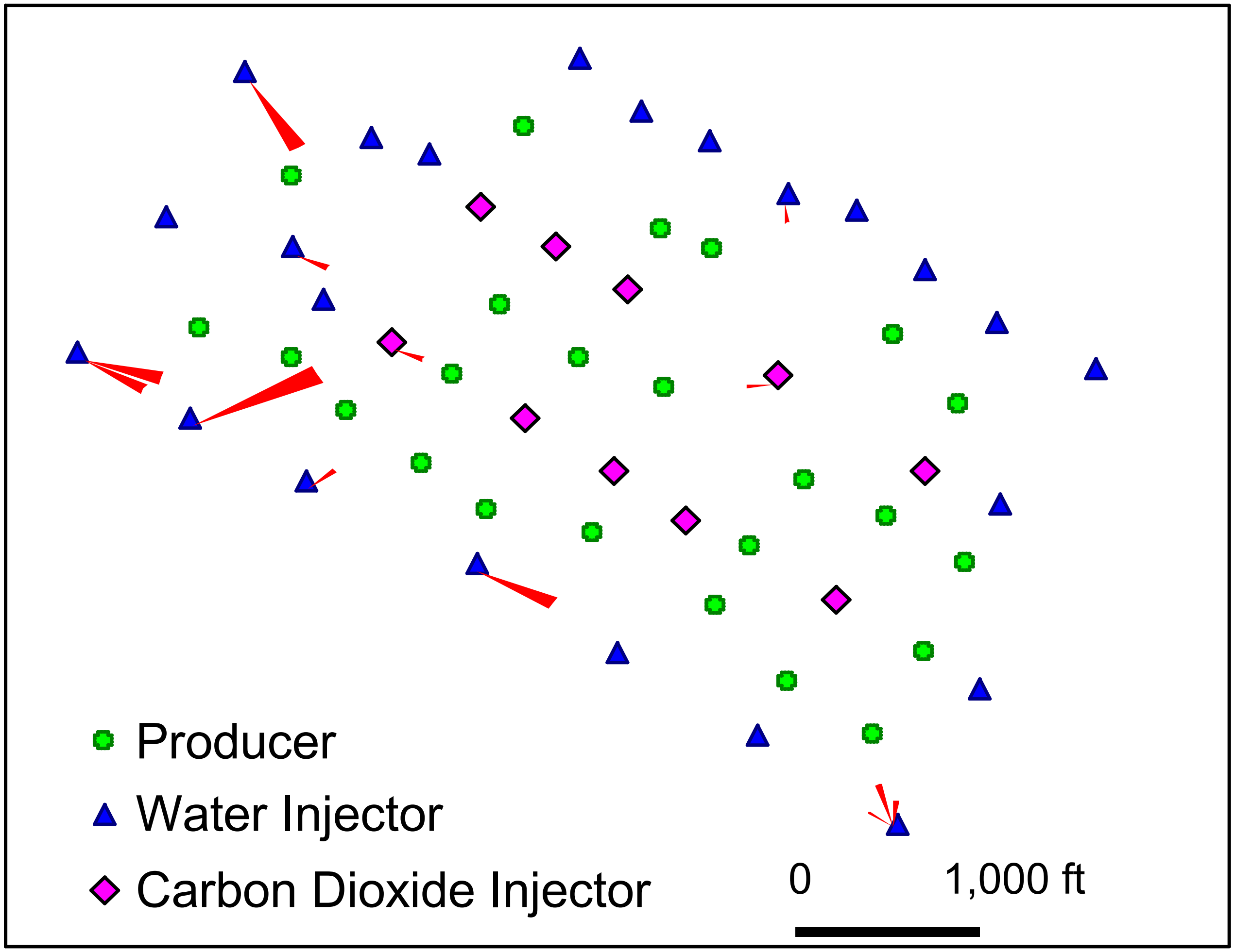
Interwell Connectivity
Two Equally Viable Solutions



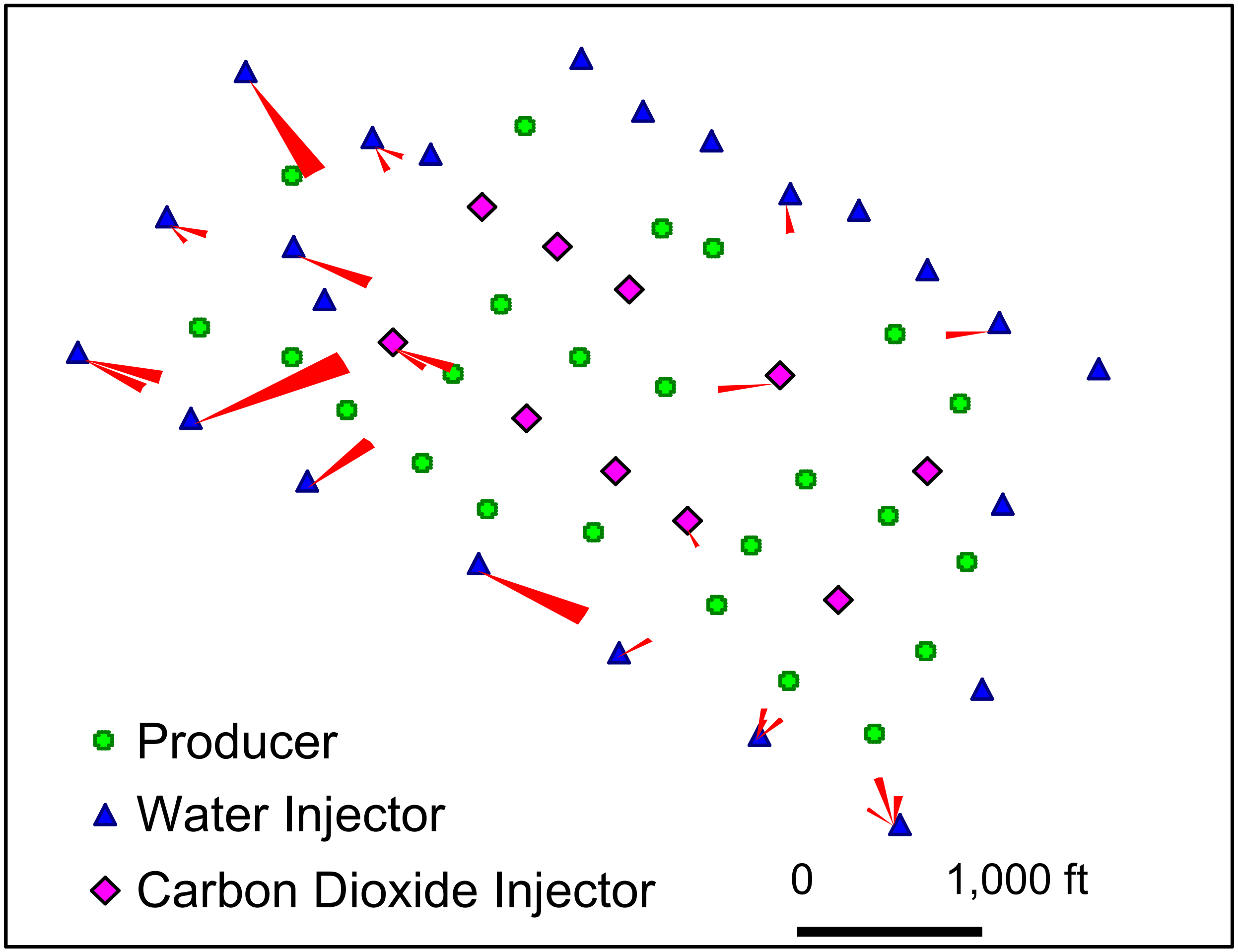
Transient Interwell Connectivity
After 10 days



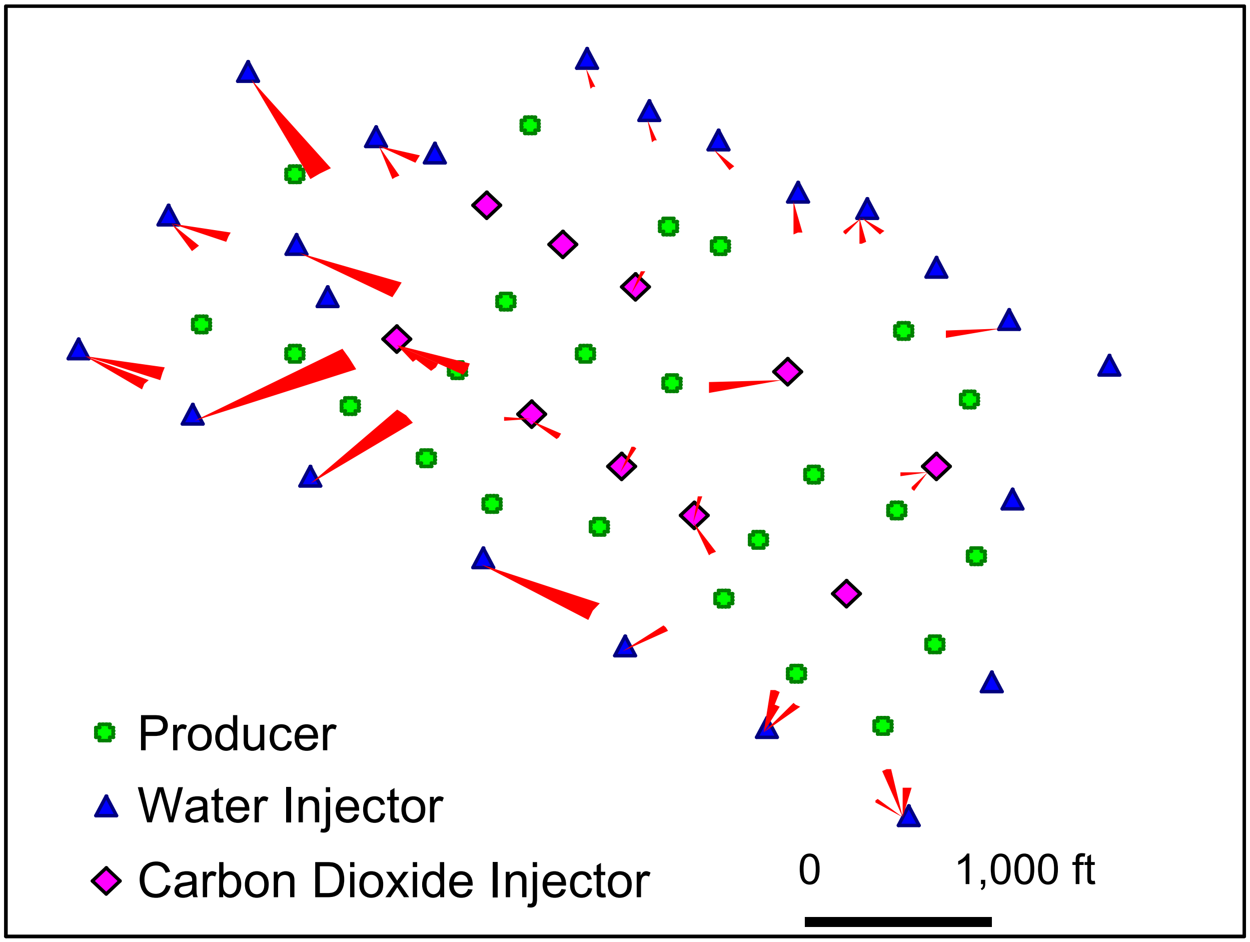
Transient Interwell Connectivity
After 30 days



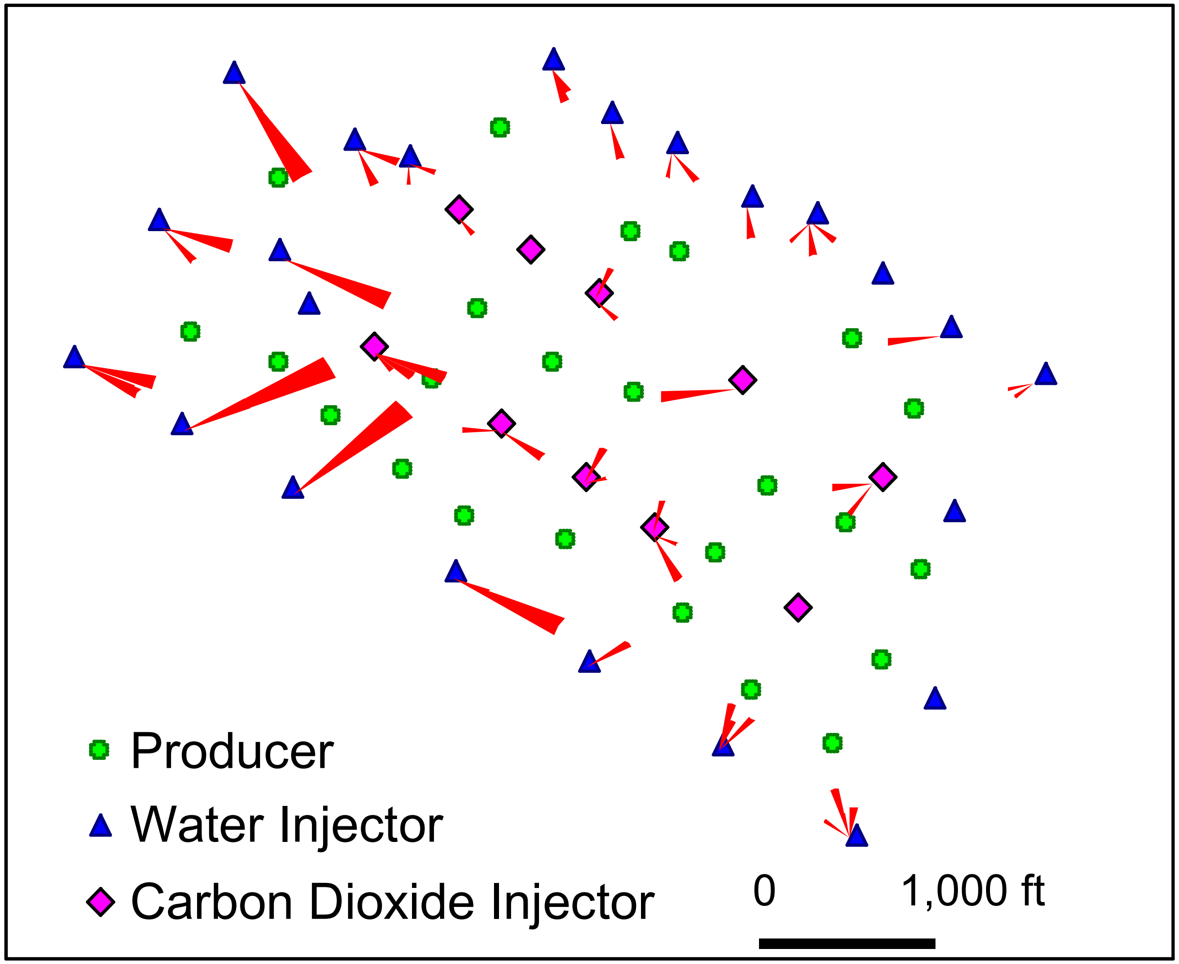
Transient Interwell Connectivity After 90 days



Transient Interwell Connectivity After 180 days



Transient Interwell Connectivity
After 365 days



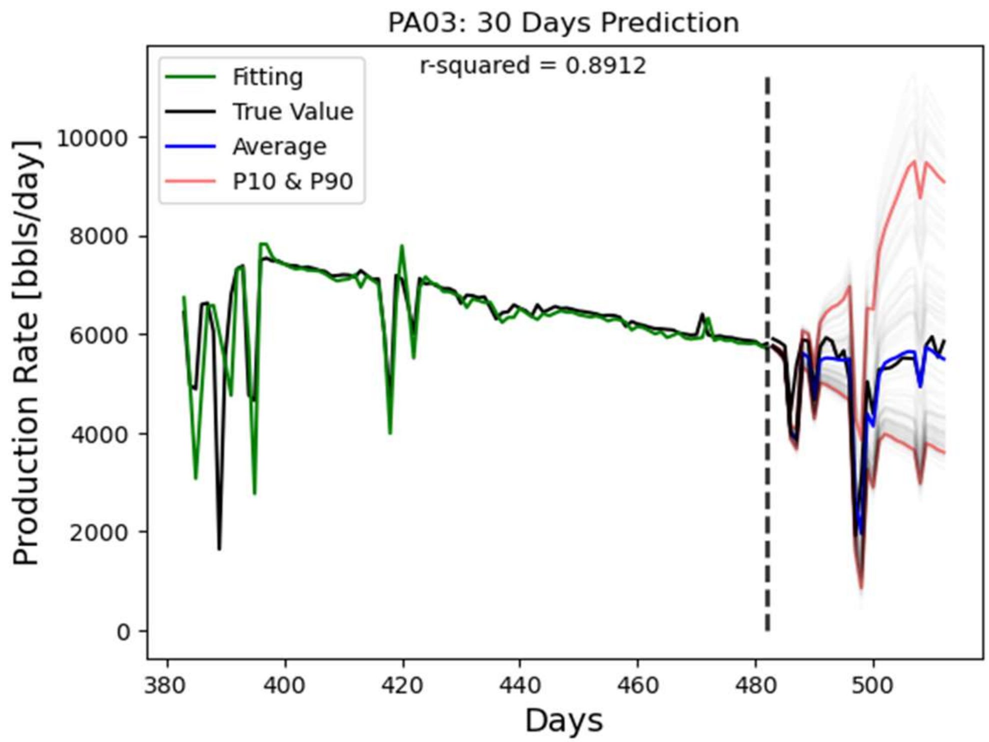
Basic Equations

Applications

- Effect of BHP
- Primary production
- CRM and tracers
- Flow capacity curves
- Oil rate modeling
- Optimization
- Tracking CO_2 front
- CRM and machine learning

ned Bootstrapping Prediction Distribution
ng CRMP with Bottomhole Pressure (BHP)

- **100 Bootstrap realizations**
- **Goodness Measure: 0.9030**
- **MSE: 260,772**



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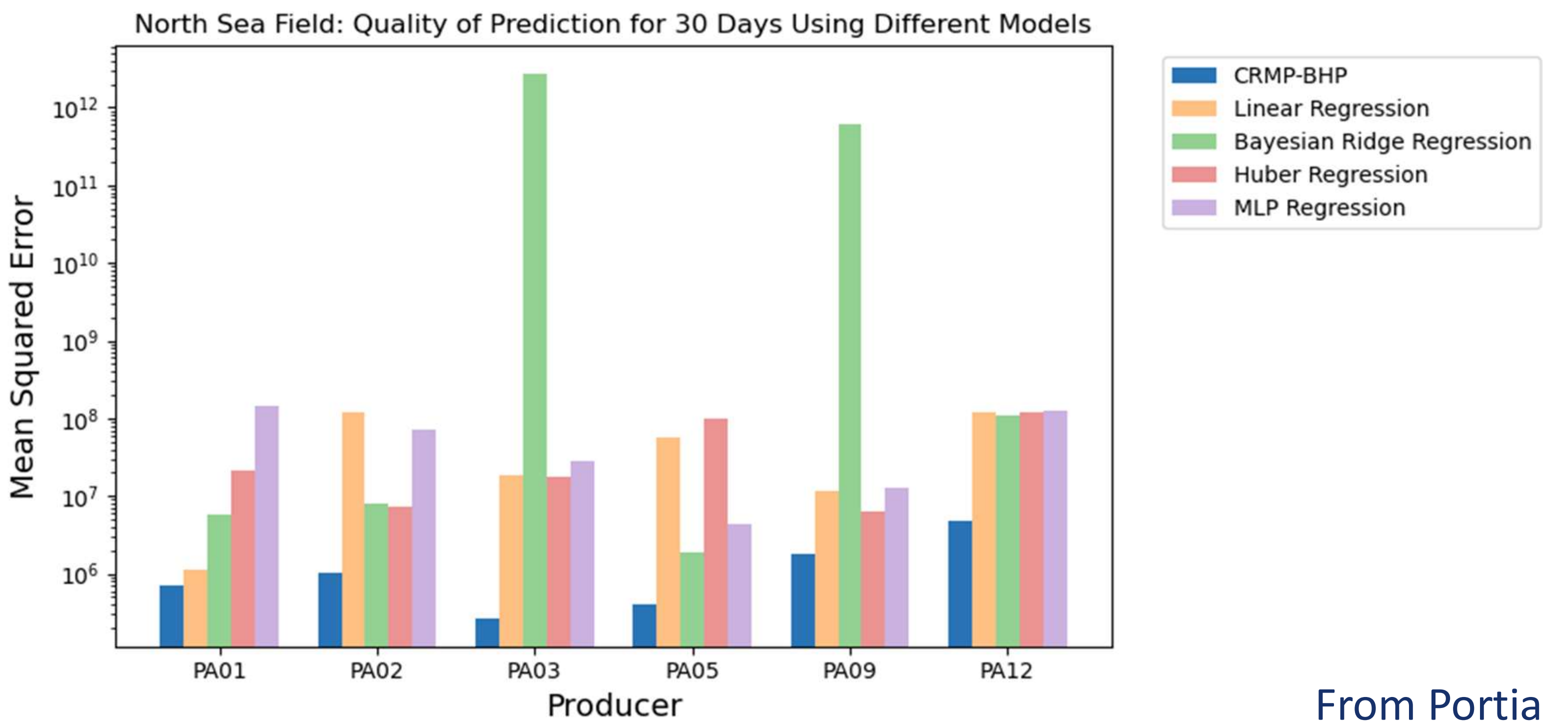
Converged Errors of Models for North Sea Field Example



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