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The SPE Foundation through member donations and a contribution from Offshore Europe

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Waterflood Design and Operational Best Practices

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Chevron

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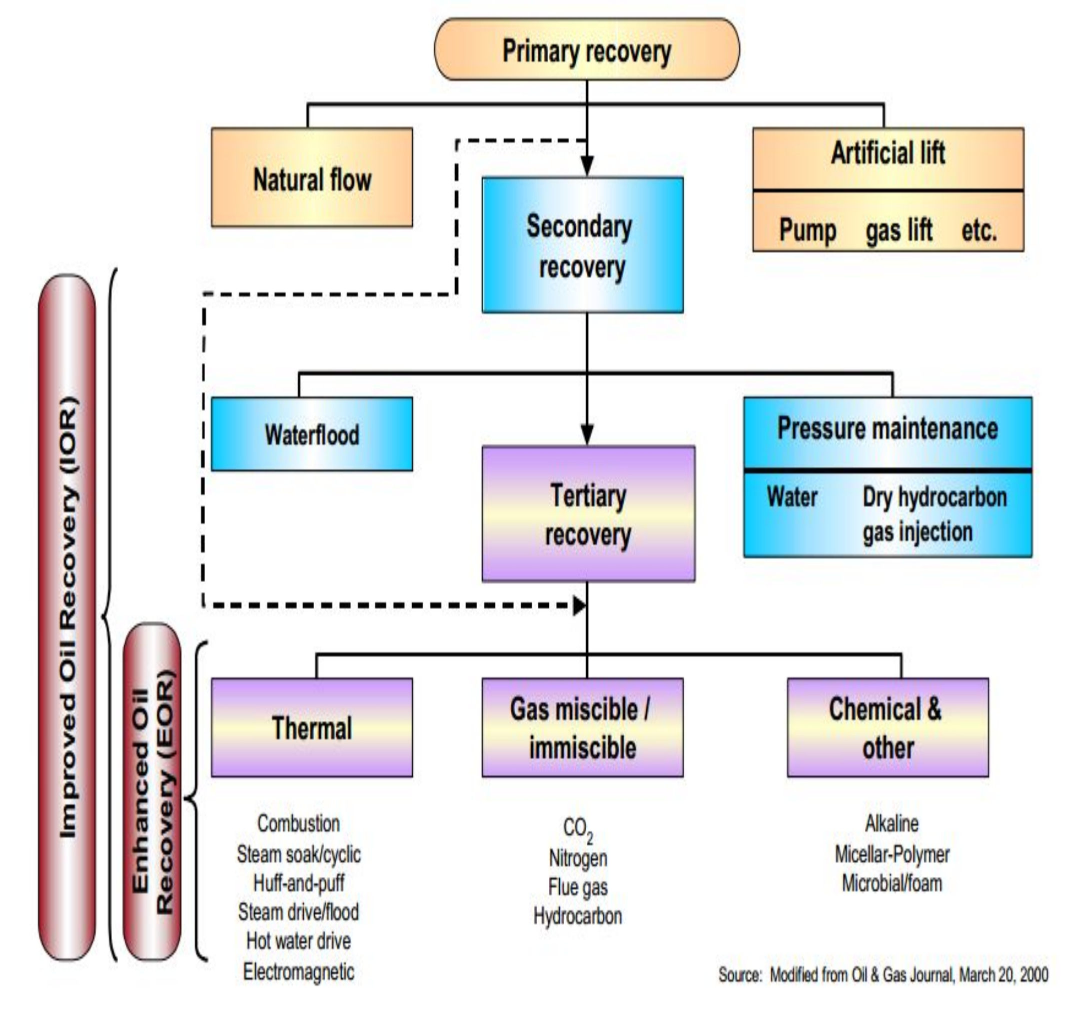
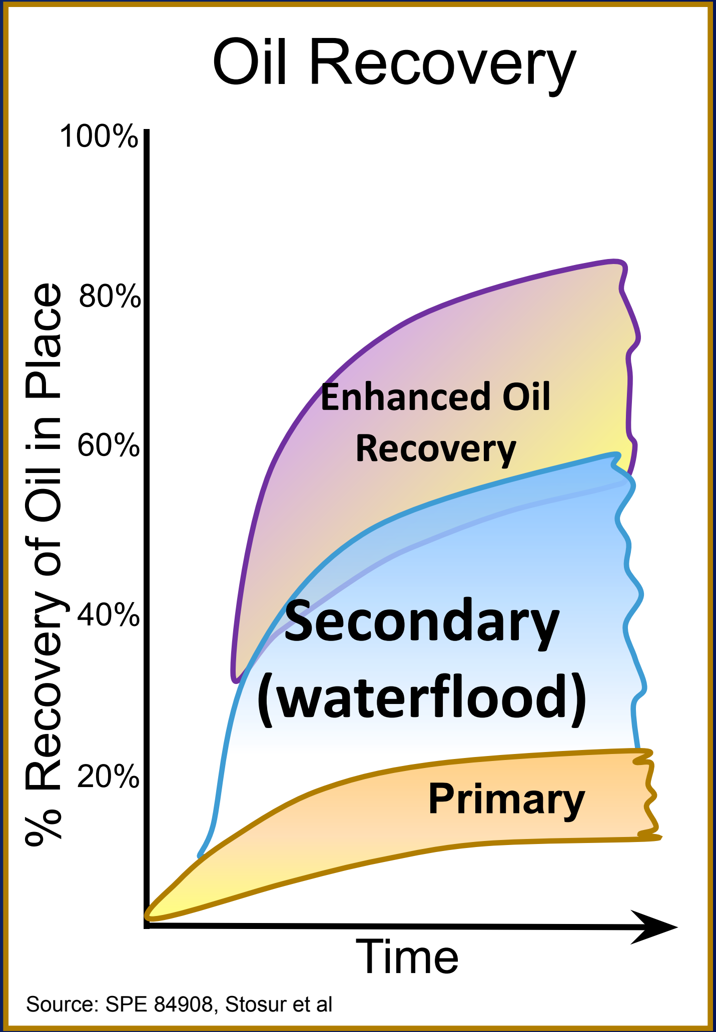
Outline

- Waterflood design life and injection efficiency
- Conformance management
- Injection well design
- Waterflood surveillance
- Water quality
- Fracturing and subsurface integrity
- Interdisciplinary aspects of waterflooding

Waterflooding: The Gateway to Enhanced Oil Recovery





Waterflood Mobility Ratio

$$M_{wf} = \mu_o k_{rw} / \mu_w k_{ro}$$

- $M_{wf} > 1$ is unfavorable – water is more mobile than oil
- $M_{wf} < 1$ is favorable – oil is more mobile than water

μ_o = oil viscosity
μ_w = water viscosity
k_{ro} = relative permeability to oil
k_{rw} = relative permeability to water

What is the Design Life of Your Waterflood?

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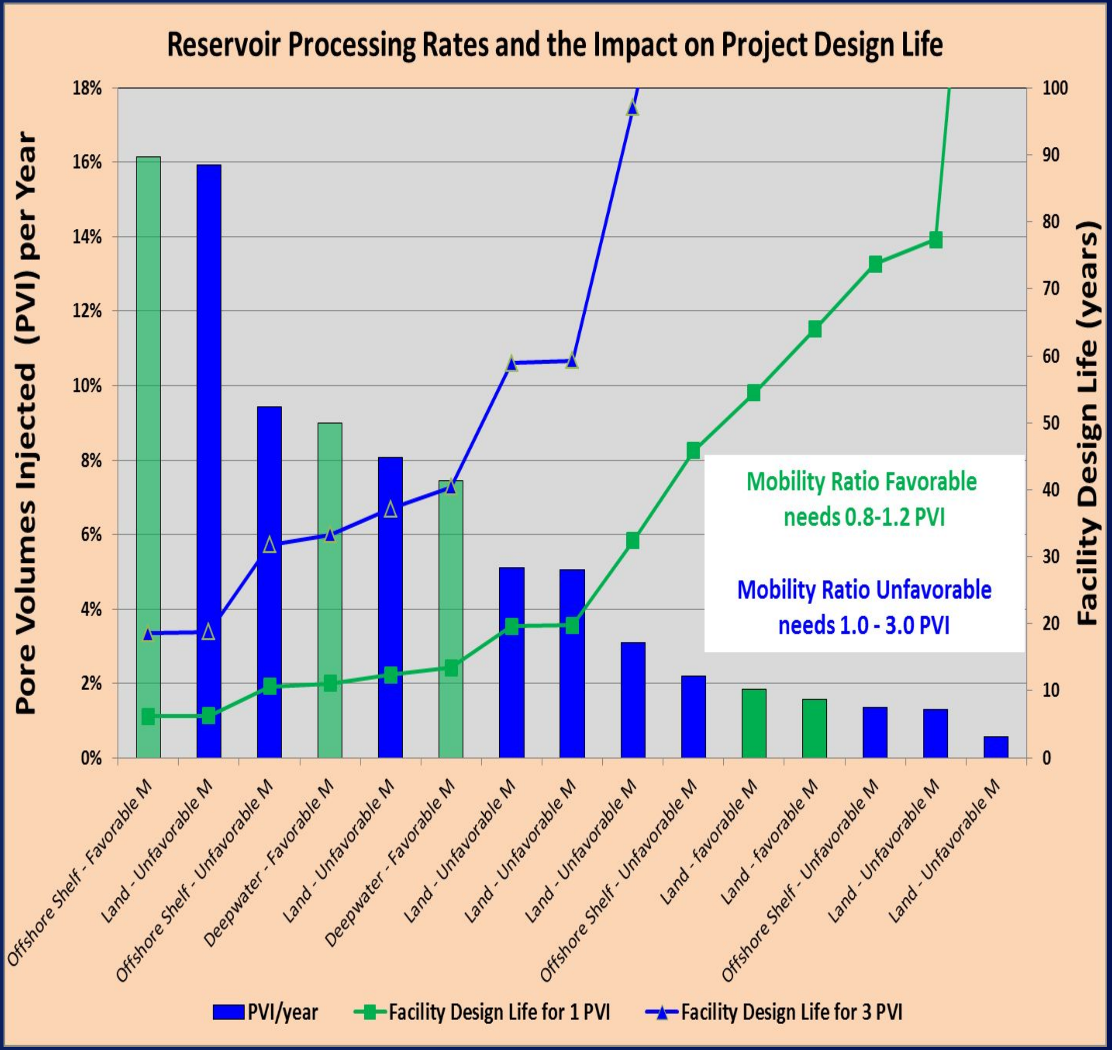
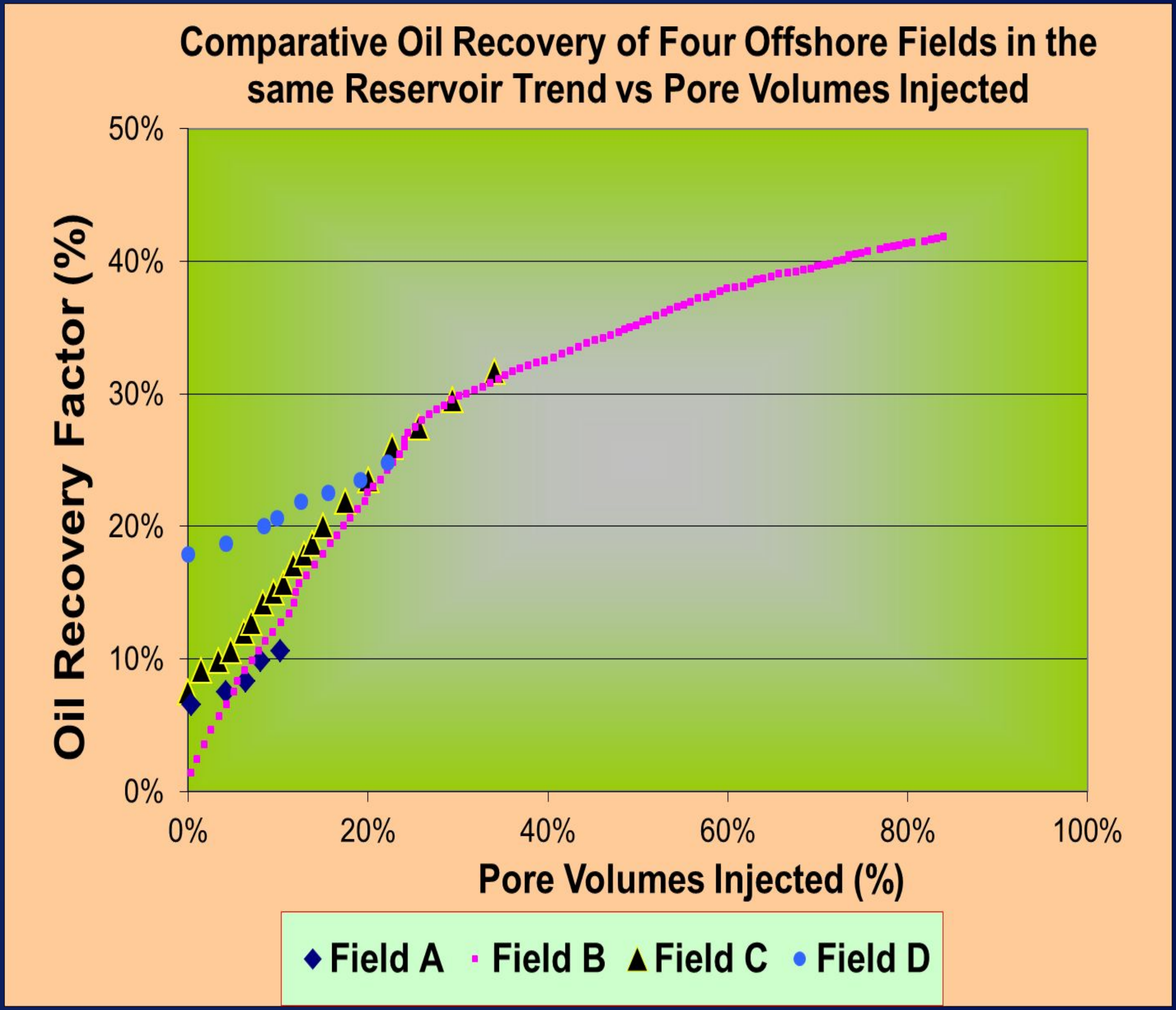
Design Life affected by:

- Mobility ratio
- Pore volumes injected (PVI) per year
- Injection efficiency
- Water quality
- Permeability
- Well spacing
- Onshore versus offshore



Case History: Pore Volumes Injected for Four Offshore Reservoirs

- Processing rates (PVI/yr) very different among fields
- Same stratigraphic unit, fluid properties, structure & trapping mechanism for all fields
- Unfavorable mobility ratio for all fields
- Communication between fields via a regional aquifer
- Start of primary production and water injection varies for each reservoir



How Efficiently Is Your Water Injection Displacing Oil?

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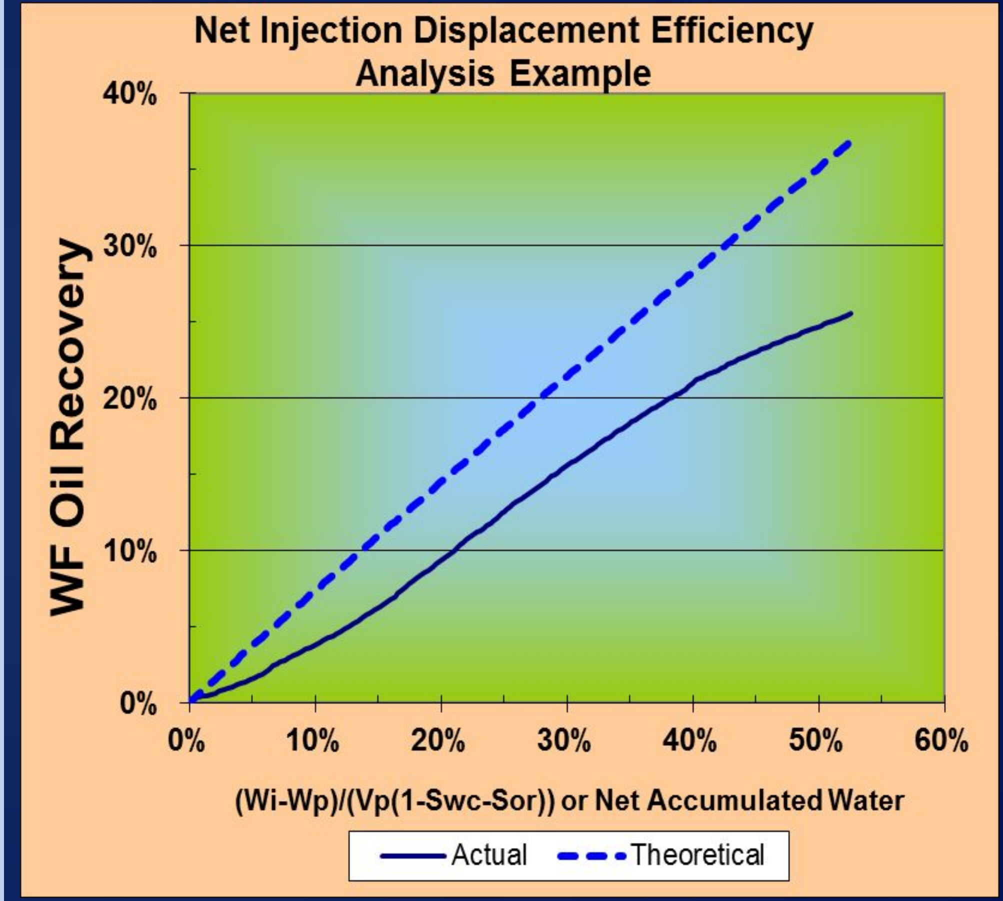
- Technique is based upon net accumulated water in the reservoir
- Projects with good injection confinement will be close to 100% efficiency (actual = theoretical)
- Injection efficiency impacts overall water requirements and facility life
- Field example to right lacks confinement and has ~75% efficiency



Reference: Staggs, SPE SW Petroleum Short Course, 1980

Voidage Replacement Ratio (VRR)

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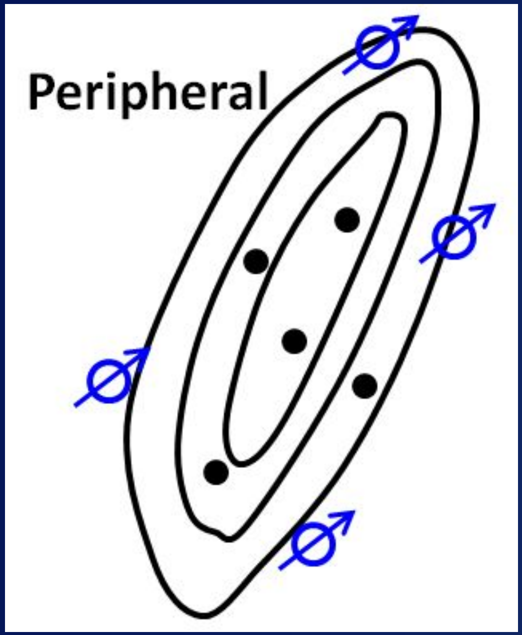
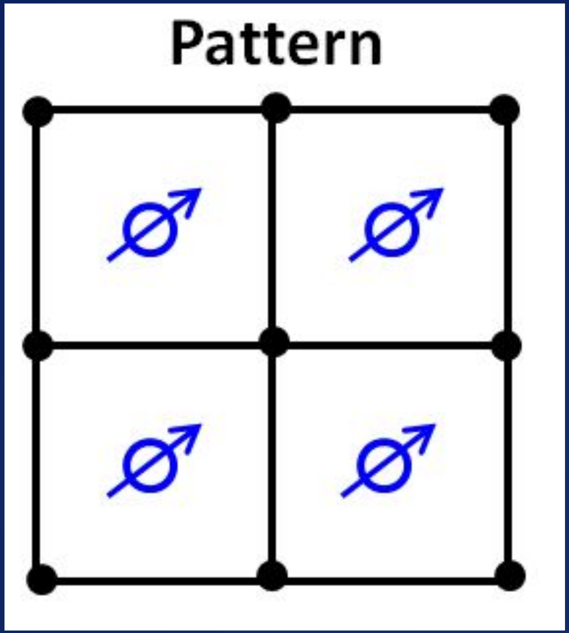
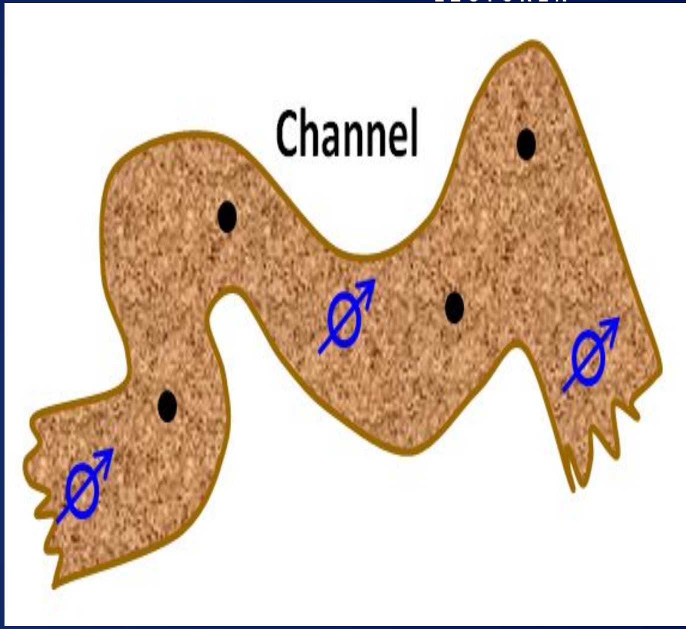
- VRR is used as a leading indicator to achieve target reservoir pressure (particularly when bottom hole pressure data is not available)
- Also known as FIFO (fluid-in fluid-out) or IWR (injection-withdrawal ratio)
- Provides accounting of reservoir barrels into and out of the reservoir
- Waterfloods should have a target, minimum, & maximum reservoir pressures

Typical VRR Values After Fill-up







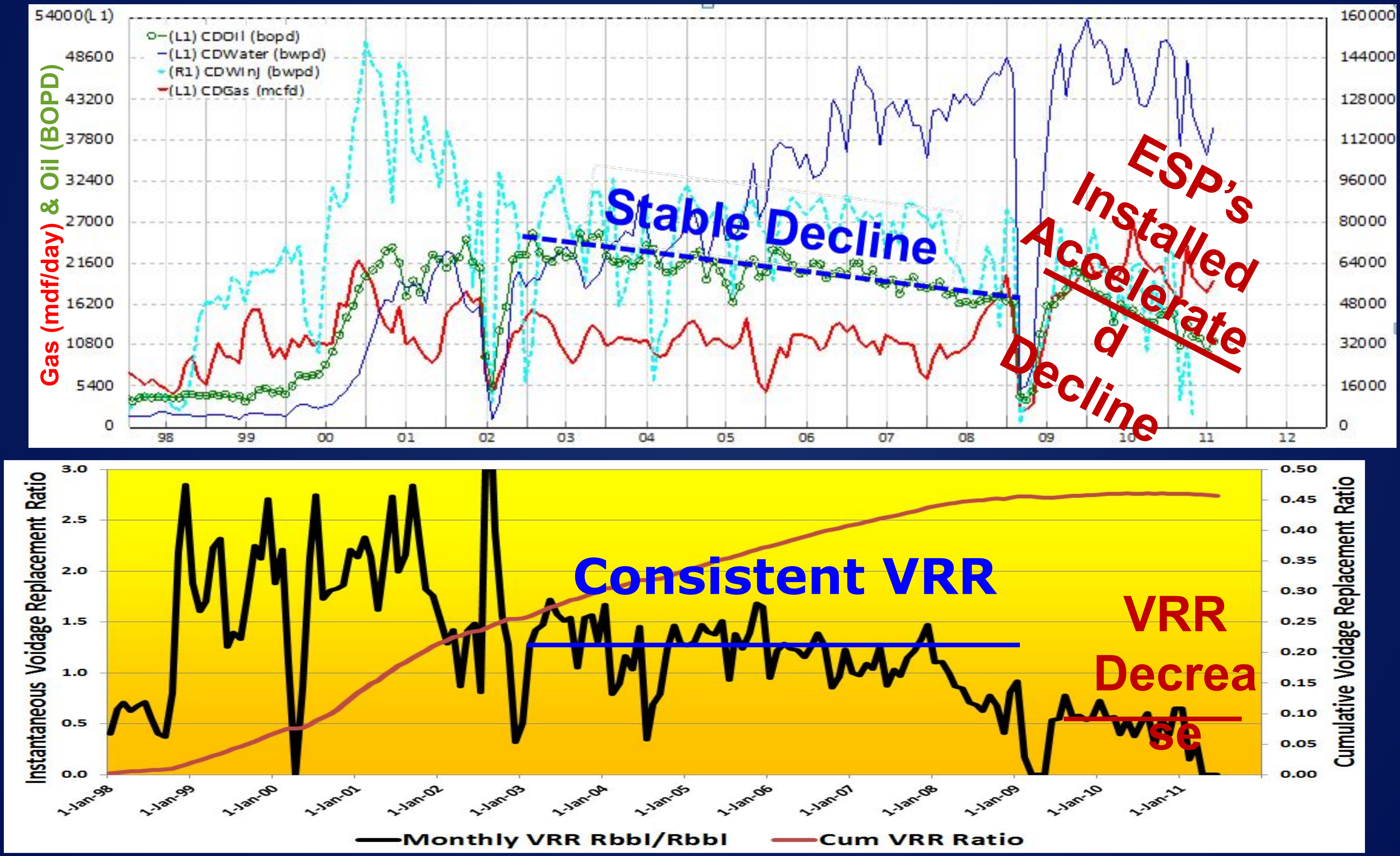
VRR 1.1 to 1.4

VRR 1.0 to 1.1

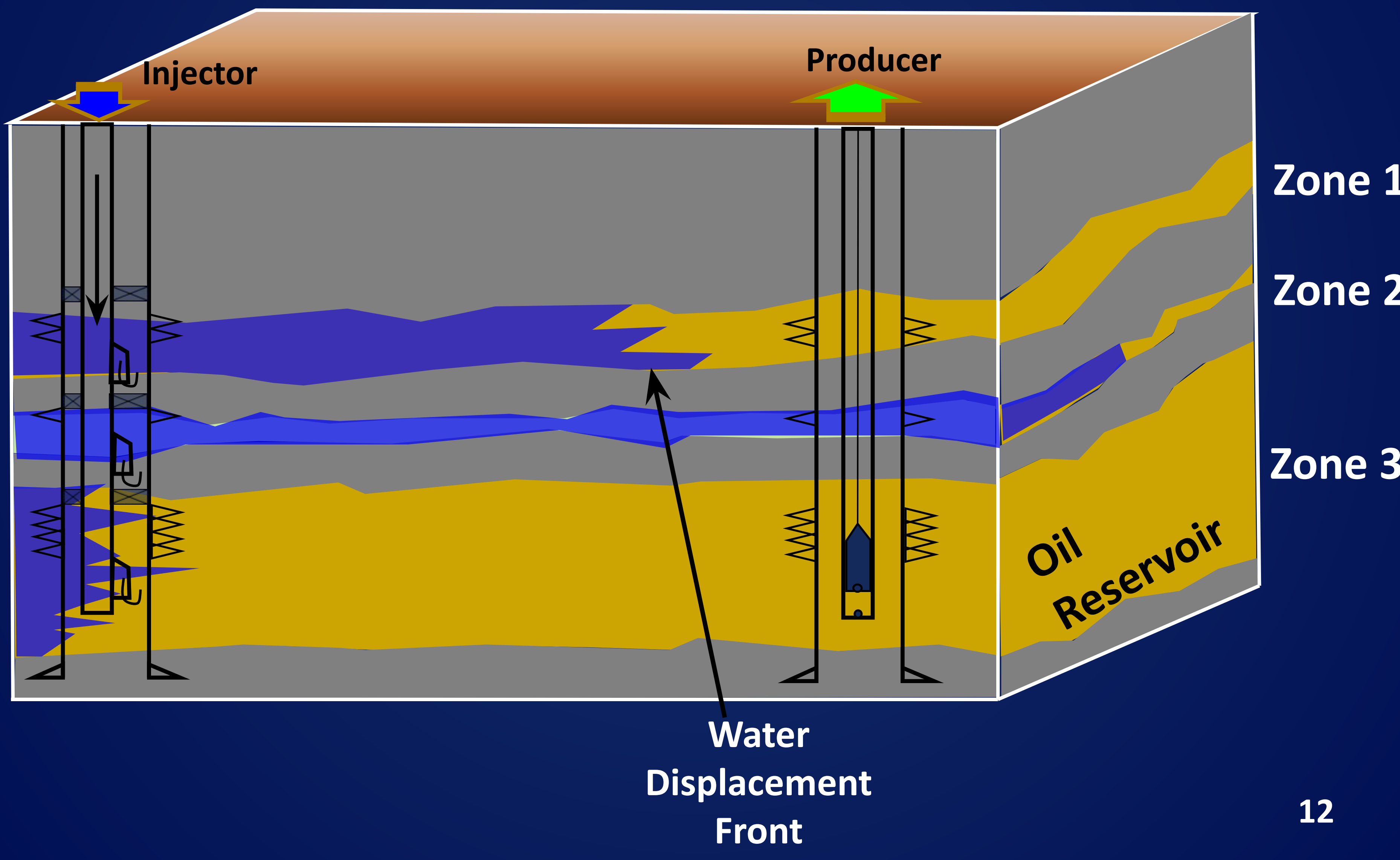
VRR 1.0 to 1.2

Do you understand your VRR requirement for your target reservoir pressure?

Importance of Voidage Replacement Ratio Management



Classic Waterflood Conformance Problem in a Layered Reservoir



Management of Layered Waterflood Response

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Flow Unit	% Original Oil In Place	% Flow Capacity (md-ft)	Current % Pore Volumes Injected	Current Water-Oil Ratio
Zone 1	25%	30%	36%	2
Zone 2	15%	50%	100%	20
Zone 3	60%	20%	10%	Dry
Total	100%	100%	30%	2.1

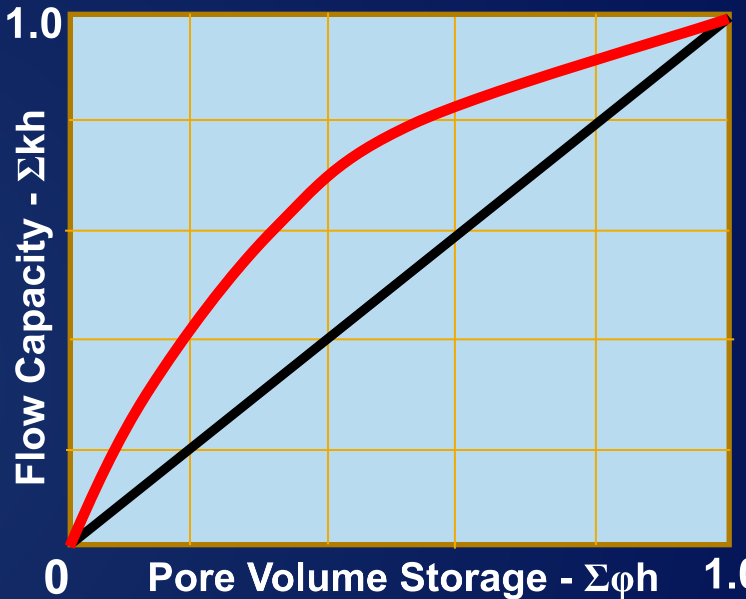
Always start with the injector if possible. Need surveillance and injector completions that enable injection profile management.

Waterflood Analysis Techniques

Identifying Injector-Producer Relationships

- Lorenz coefficient – Dykstra-Parsons
- Capacitance-resistance models (CRM)
- Streamtube or streamlines
- Electromagnetic surveys
- Gravimetric surveys

Lorenz Plot



1950, Schmalz and Rahme

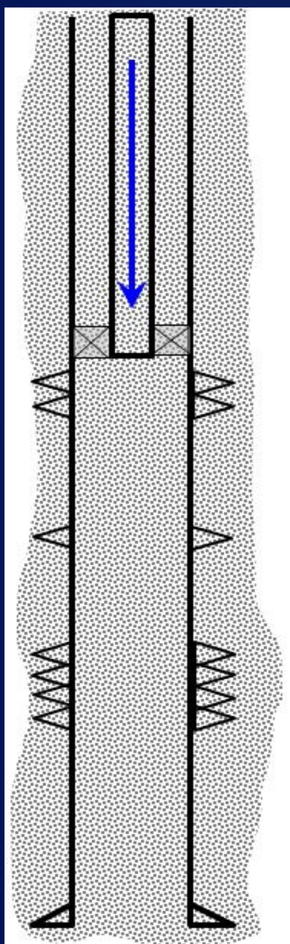
Understand Critical Assumptions of Each Technique

- Single hydraulic flow unit or averaging of multiple hydraulic units - 2 dimensional only
- Material balance – confinement of injection and production
- Many waterfloods do not honor these simple assumptions

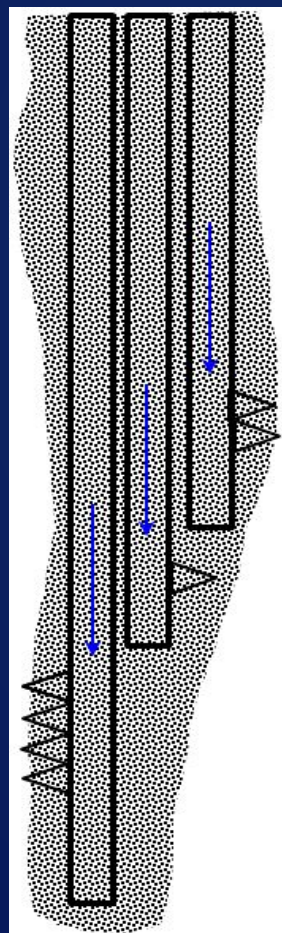
Reference: SPE 23451, 30758, 59529, 68802, 84080, 102478, 114983, 124625, 129604, 171226, 176569, 177106, IPTC 17978, & SEG 2002-0791

Injector Completions for Conformance Control

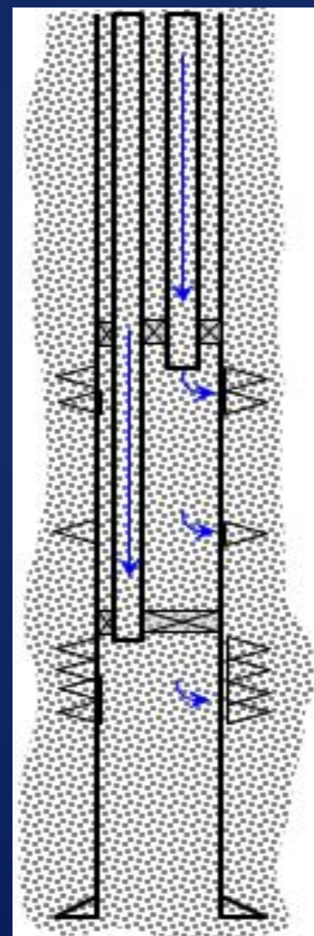
Limited Entry Perforating



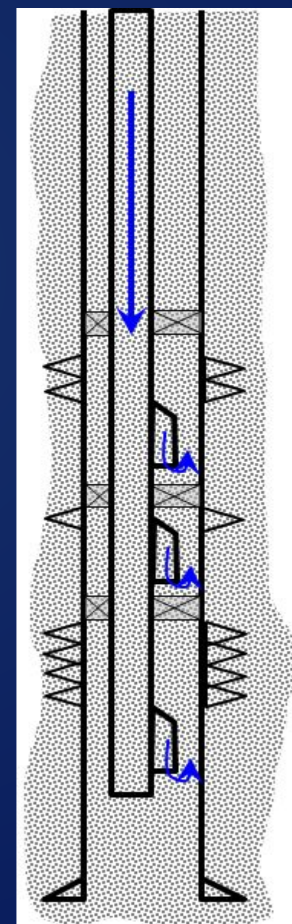
Dedicated Tubingless Slimhole



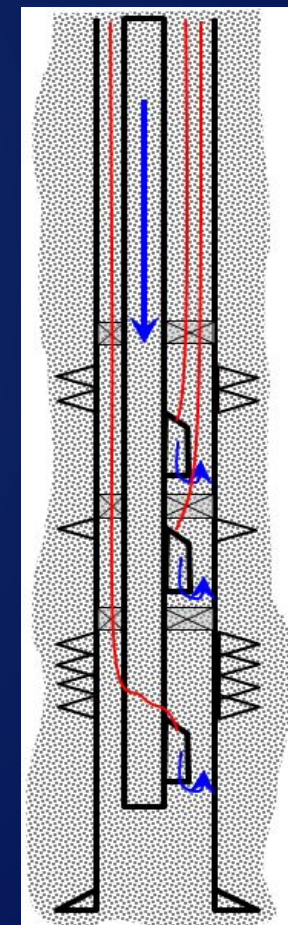
Dual String Injection



Packers & Injection Mandrels with Chokes



Smart Injector with Packers & ICV's



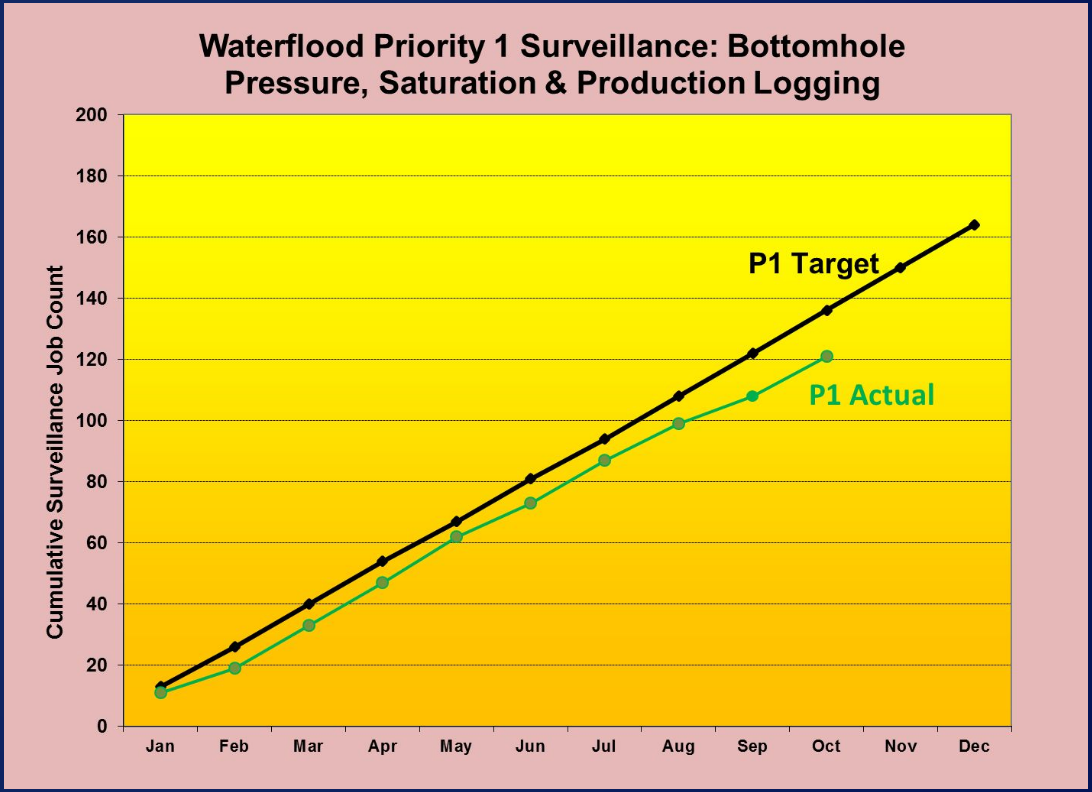
Elements of a Waterflood Surveillance Plan

Required Routine Surveillance :

- Production testing
- Injection measurement
- Water quality
- Surface & bottomhole pressures
- Production and injection logging
- Well mechanical integrity

Non-Routine Surveillance:

- Pressure transient analysis
- Seismic
- Saturation logs
- Openhole logs in new wells
- Interwell tracers
- PVT Sampling
- Formation testing in new wells
- Routine & special core analysis
- Extended leakoff test (XLOT)



Emerging Technology: Fiber Optic Distributed Acoustic Sensing (DAS) for Injection Flow Profiling

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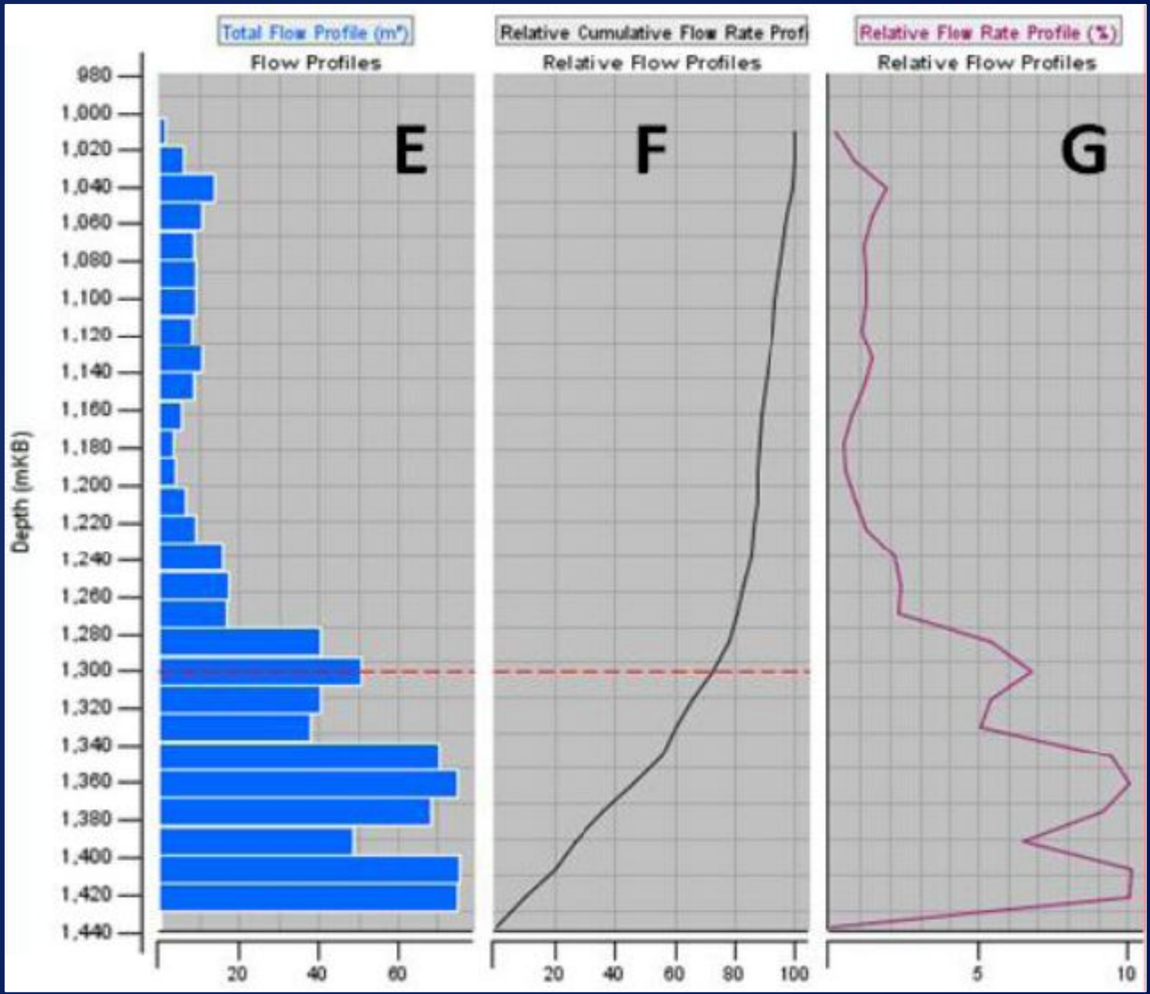
- Fiber optic distributed temperature sensing (DTS) is established technology for flow profiling.
- DTS flow profiling has limitations when temperature differentials are small in horizontal wells.
- DAS flow profiling algorithms are improving rapidly.
- Consider equipping injectors and producers with capillary tubes for fiber optic flow profiling.



Cross-functional Waterflood Management

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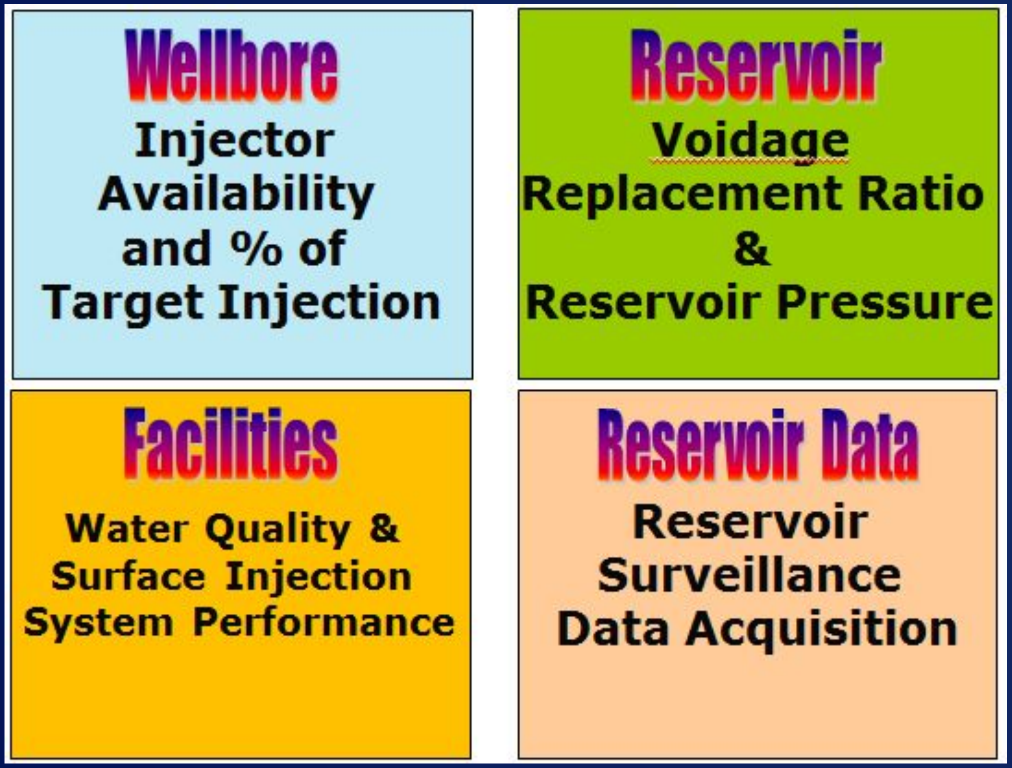
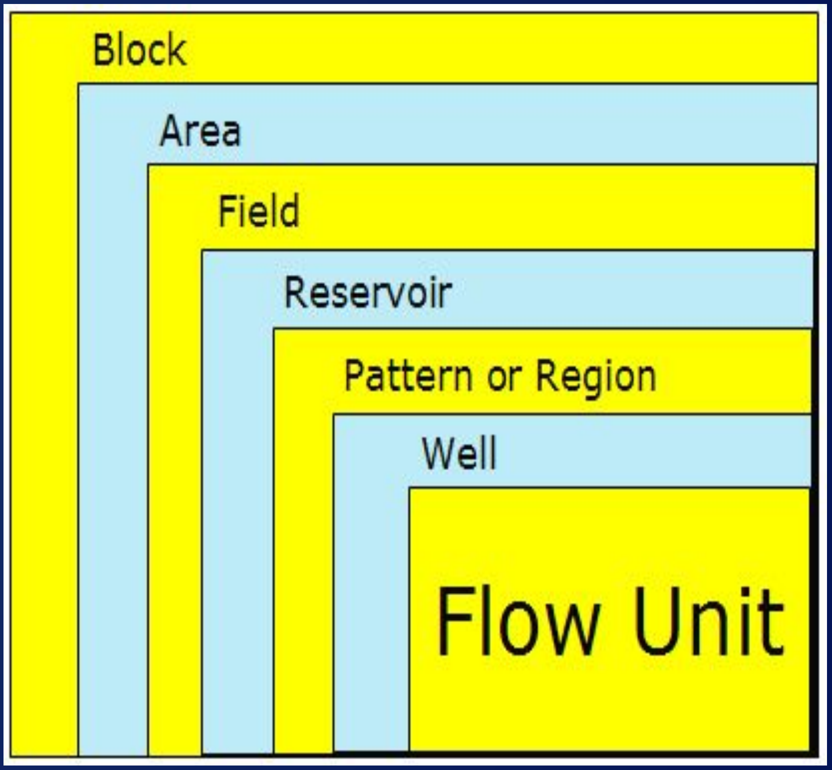
Waterflood Scorecards



Hierarchy of Analysis



It takes more than just reservoir & production engineers to have a successful waterflood

Typical Water Quality Specifications

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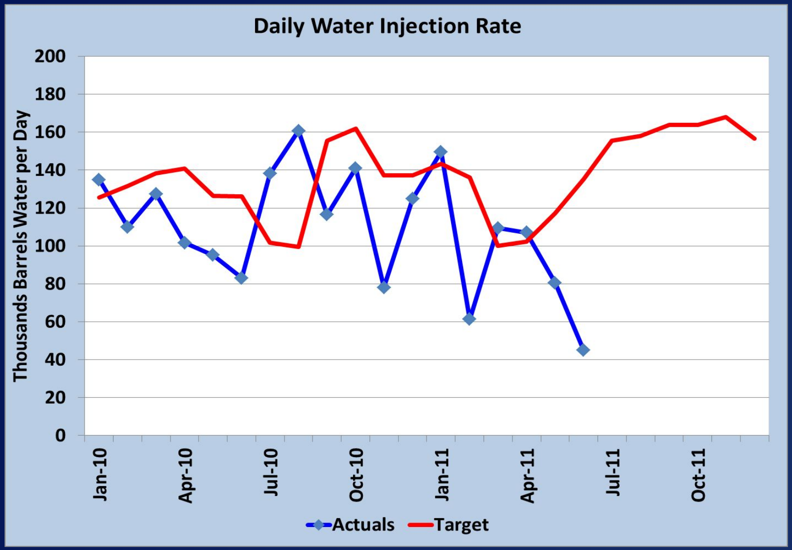
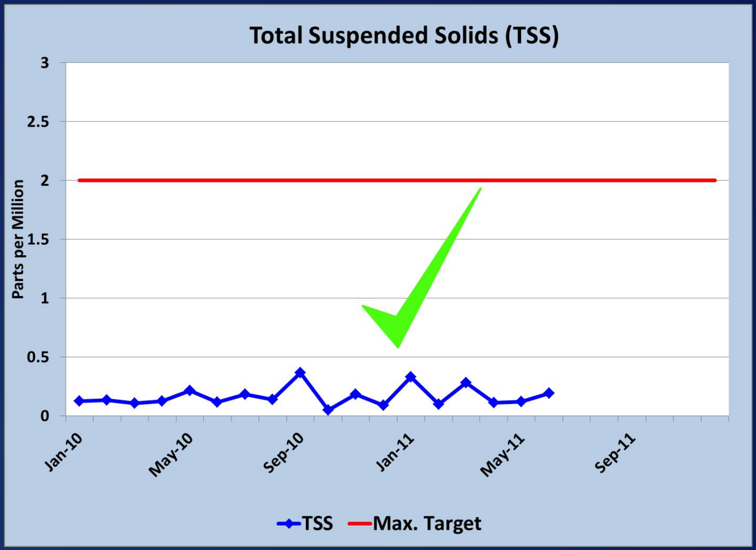
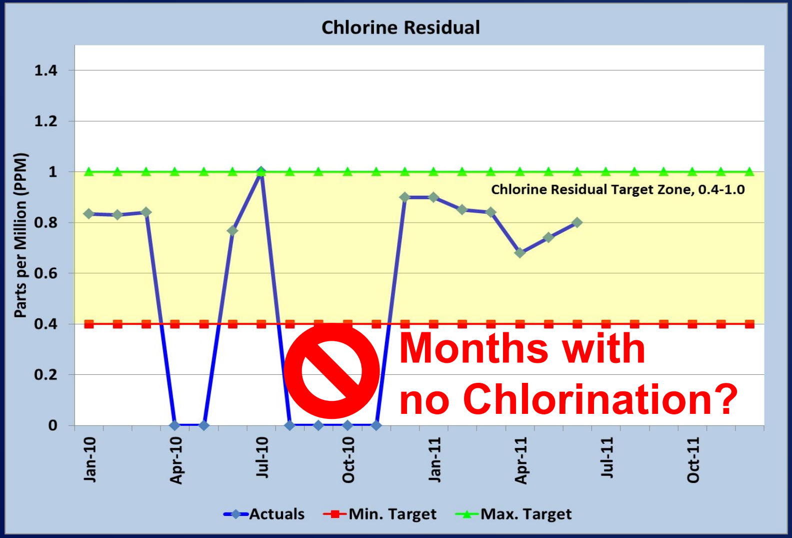
Parameter	Typical Specifications
Total Suspended Solids	< 2 ppm
Dissolved Oxygen	< 10 ppb
Sulfate Content	< 2 to 40 ppm
Chlorine residual	0.3 – 1.0 ppm
Sessile Sulfate Reducing Bacteria	< $100/cm^2$
Planktonic sulfate reducing bacteria	<100/mL

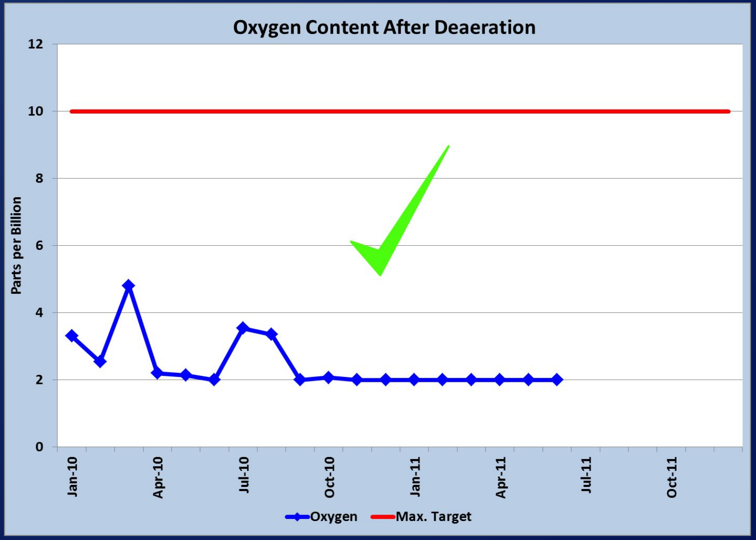
Reference: NACE 5962 Eggum et al 2015, IJAETCS Abdulaziz 2014, & SPE 98096 Jordan et al 2008

Offshore Water Injection Plant Scorecard









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Biofouling: Consequences of Not Meeting Water Quality Specifications?

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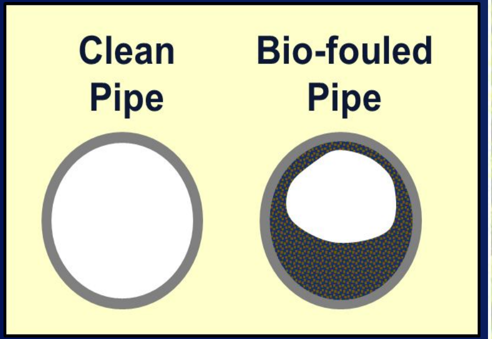
What are Biofilms?

They are collections of microorganisms and the extracellular polymers they secrete. They attach to either inert or living substrates. These bacteria are classified as planktonic (free floating) or sessile (anchored).



MIC Injection Tubing Corrosion Example

Microbiologically Induced Corrosion (MIC): Bacteria produce waste products like CO_2, H_2S, and organic acids that corrode the pipes by increasing the toxicity of the flowing fluid in the pipeline. The microbes tend to form colonies in a hospitable environment and accelerate corrosion under the colony.

Under Deposit Corrosion: Consequences of Not Meeting Water Quality Specifications?

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- A common corrosion mechanism in water injection systems with biofouling or solids accumulation.
- The deposit creates “cell corrosion,” which is typically very aggressive and localized.
- Deep penetration of steel can occur rapidly under deposit

Pipeline Under Deposit Corrosion

Reference: NACE 11266, 2011

Oxygen: Consequences of Not Meeting Water Quality Specifications?

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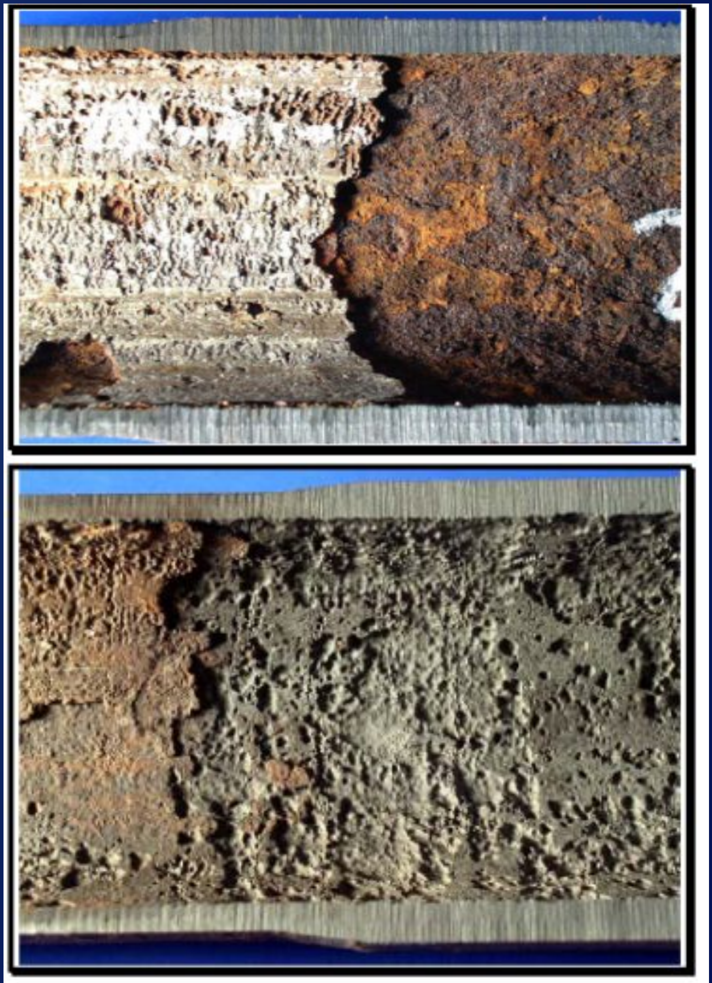
- Bare carbon steel can provide long-term waterflood service in the absence of oxygen
- Oxygen is a strong oxidant and reacts with metal very quickly.
- Oxygen magnifies the corrosive effects of the acid gases H_2S and CO_2.

Oxygen Corrosion Examples



Water Injection Plant (WIP) Operations

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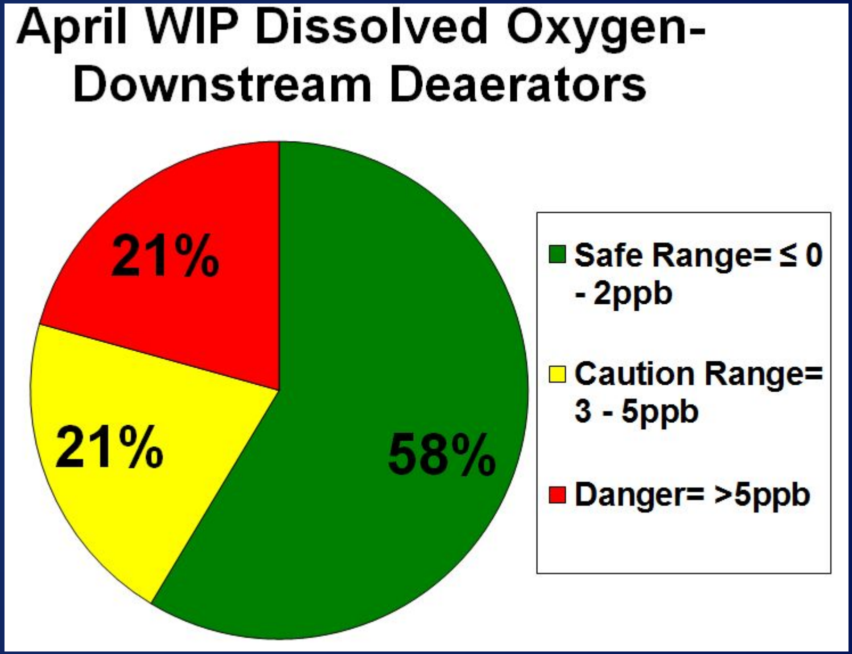
- Are your water injection plant operations lower priority relative to oil & gas plant operations?
- Operations staff in a difficult position: Do they meet a water volume target or a water quality specification?
- Cross functional discussion is required to make the best decision for overall waterflood management.



Operational Discipline with Water Quality

- Do you have a water quality specification or a water quality suggestion?
- Do you have quality criteria for stopping water injection?
- The negative impacts of off-spec water are not reversed with pigging, acidizing, chemical shock treatments, surface piping replacement, etc.

Corrosion Byproducts: Oily Iron Sulphide and Iron Oxide in an Injector

Off-spec water today is not corrected by on-spec water tomorrow.

Matrix Injection Myth in Waterfloods

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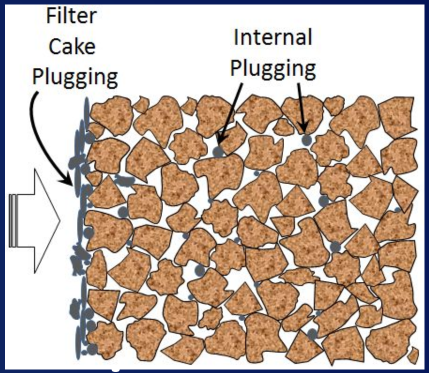

- Long term matrix injection cannot be achieved with practical water quality levels in sandstone reservoirs.
- Some near wellbore fracturing will occur in most injectors due to thermal stress & plugging effects.
- Injection pressures, rates and water quality can be used to manage fracture geometry.
- Vuggy, fractured carbonates can be an exception

See SPE 28082, 28488, 39698, 59354,84289,95021, 95726, 102467, 107866,165138, et al

Subsurface Integrity Management for Waterfloods

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- Subsurface integrity management ensures injected fluids are confined to targeted and permitted reservoirs.
- Industry events with injection water breaching seabed or earth's surface
- Increasing societal and governmental concerns
- Historical focus has been on understanding reservoir fracturing and not the overburden and caprock.
- Keeping injection pressures below caprock fracture pressures does not guarantee containment – geomechanical modeling may be required.

Key Takeaways

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- Understand the design life and processing rate of your reservoir (PVI/year)
- Understand how much of your water injection is effective
- Plan for early water breakthrough and layered reservoir management
- Understand surveillance minimums and emerging fiber optic technologies
- Use operational discipline with your water quality, have criteria for stopping injection , know your water chemistry
- Plan for injector fracturing and subsurface integrity management
- Use a cross functional/interdisciplinary team approach

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