Density effects in Aquifer Storage & Recovery

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Centre for Groundwater Studies

CSIRO

ASR – definition

- Injection occurs during surplus of fresh surface water
- Freshwater is stored in aquifer
  (here assume confined)
- Water is recovered when needed

ASR in the literature

- Cederstrom (1947)
- Bear & Jacobs (1965)
- L.S.U. – various authors (1967-75)
- Merritt (1983)
- Pyne (1995)
- Now many operational sites worldwide
  - eg Salisbury, SA

Expected water losses

- In brackish / saline groundwater:
  - Dispersive mixing with salty groundwater
  - Flow due to regional hydraulic gradient
    - Recovered water is of unsatisfactory quality
    - Recovery may need to be ***terminated prematurely***
    - If much less water is extracted than was injected:

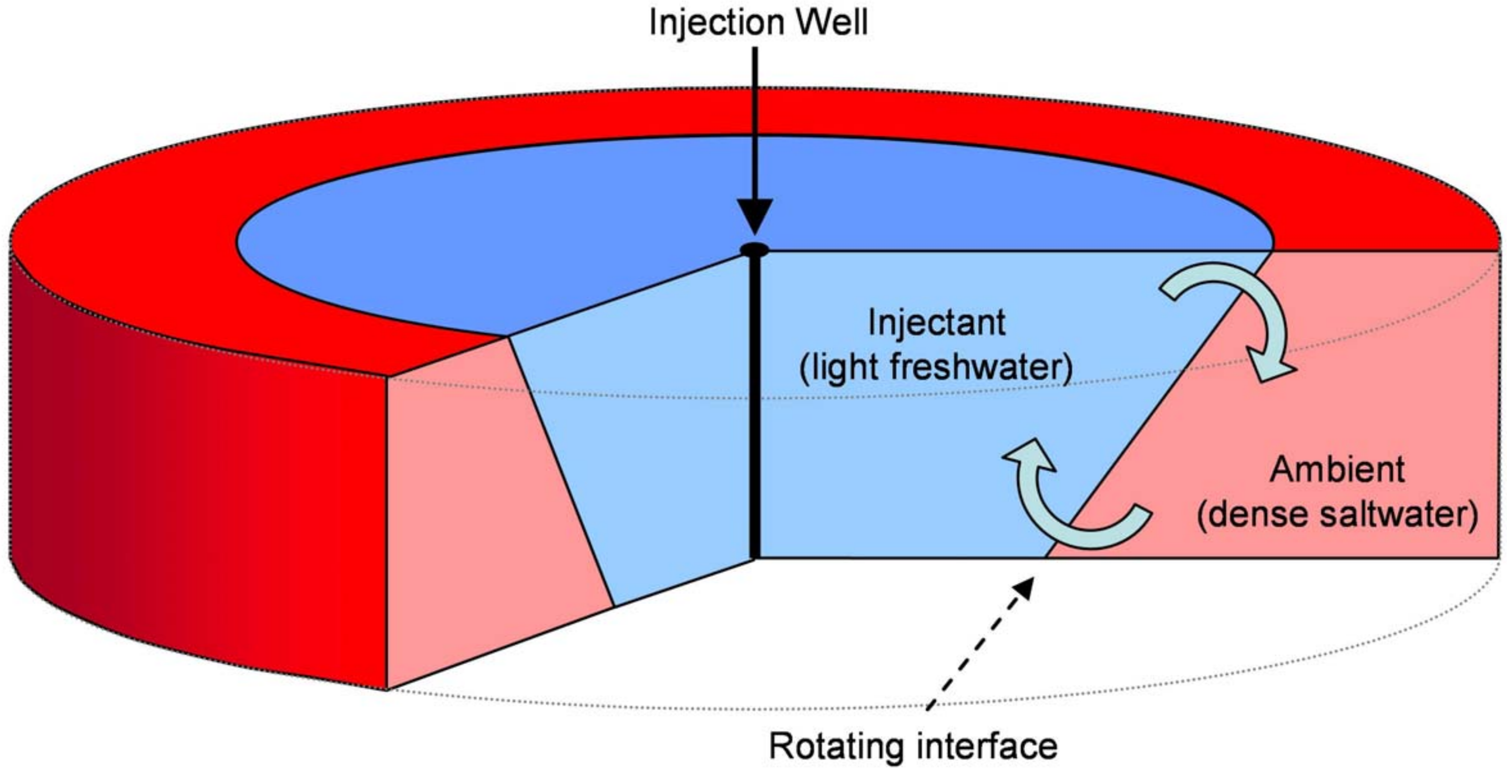
LOW RECOVERY EFFICIENCY

$$RE = \frac{V_{extracted}}{V_{injected}}$$

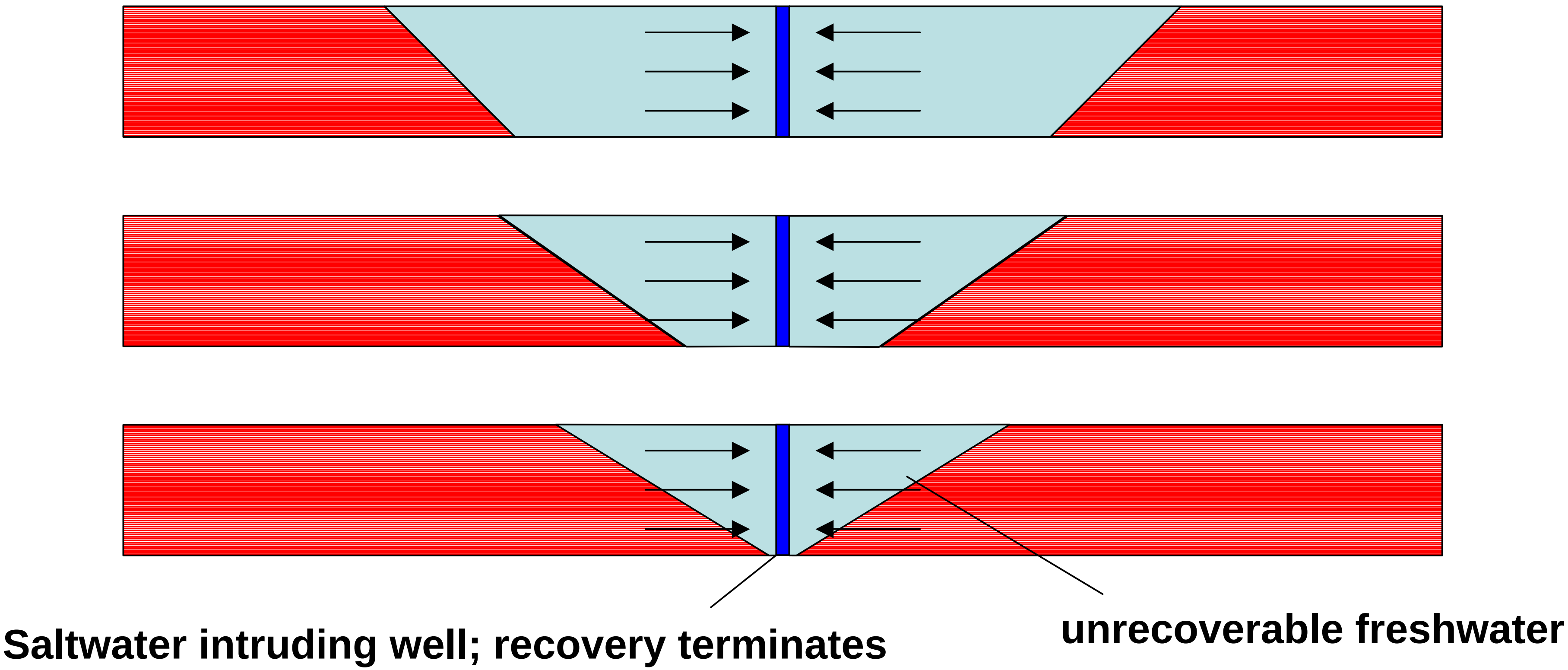
Water losses due to density

- Density-induced tilting of interface
  - “Buoyancy stratification”
  - “Gravitational segregation”
- L.S.U. – Esmail & Kimbler (1967) and others
  - Empirical method: function of permeability, density contrast, aquifer thickness, mixed zone width
  - ***Assumed tilting only occurs significantly during storage***

Density effects in ASR



Interface tilting can reduce recovered volume of freshwater:



Focus of this investigation

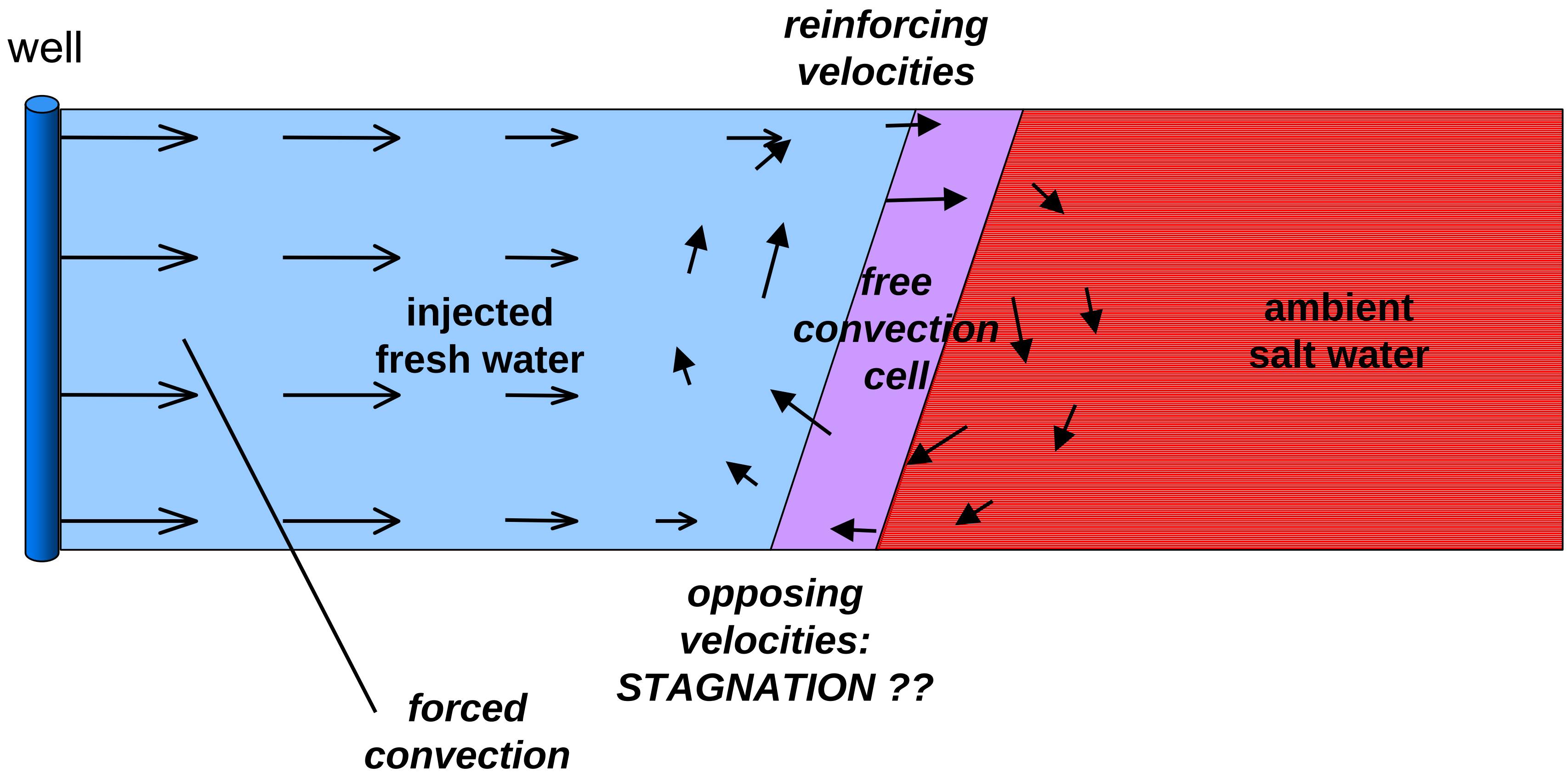
- ***Mixed convection*** analysis
  - Forced convection (pumping)
  - Free convection (density-induced flow)
- Study influence of density in all 3 phases (***injection***, storage, ***recovery***)

Why the investigation?

- Mixed convection not studied previously
- Need more comprehensive decision criteria for consideration of density effects
- What parameters are important?
  - More than **just** a critical ΔC **???**
  - Pumping rates?
  - What else?
- ***Which situations require density-dependent analysis???***

Mixed Convection

- Superposition of forced convection & free convection during injection and recovery



Characterising convection processes

- Forced convection due to pumping:

  use idealised velocity

$$v_{forced} = \frac{Q}{2\pi r \varepsilon B}$$

(this was derived from the volume of a cylinder)

- Free convection due to density:

  use Darcy's Law

$$v_{free} = \frac{K}{\varepsilon}\frac{\Delta\rho}{\rho_0}$$

(this is simply the density-dependent term in Darcy's Law)

Characterising ***mixed convection***

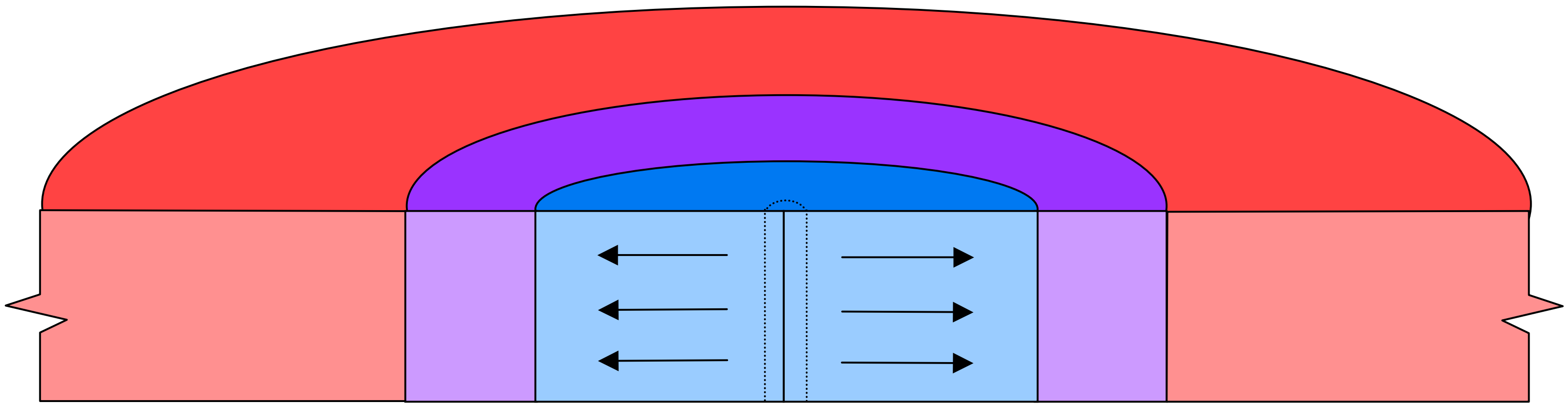
- Define "Mixed Convection Ratio" as ratio of previously defined velocity terms:

$$M = \frac{v_{free}}{v_{forced}} = \frac{2\pi rB}{Q} \frac{K\Delta\rho}{\rho_0}$$

- Rough and ready, but it's a starting point that considers major parameters in ASR
- Assist "back-of-the-envelope" decisions

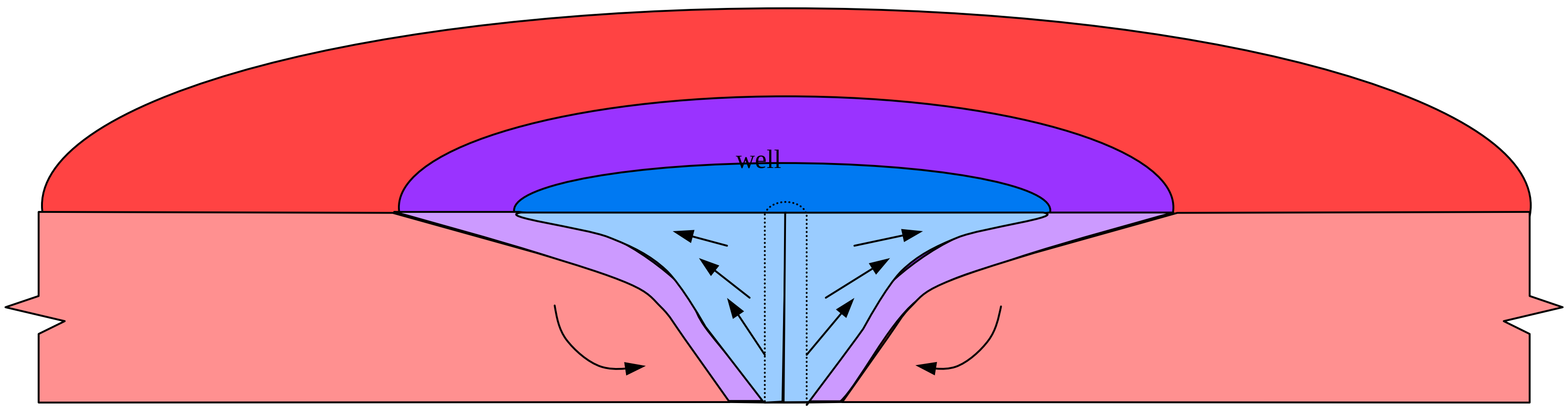
Expectations

- High injection rate and low density contrast: M << 1
  - Forced convection dominated

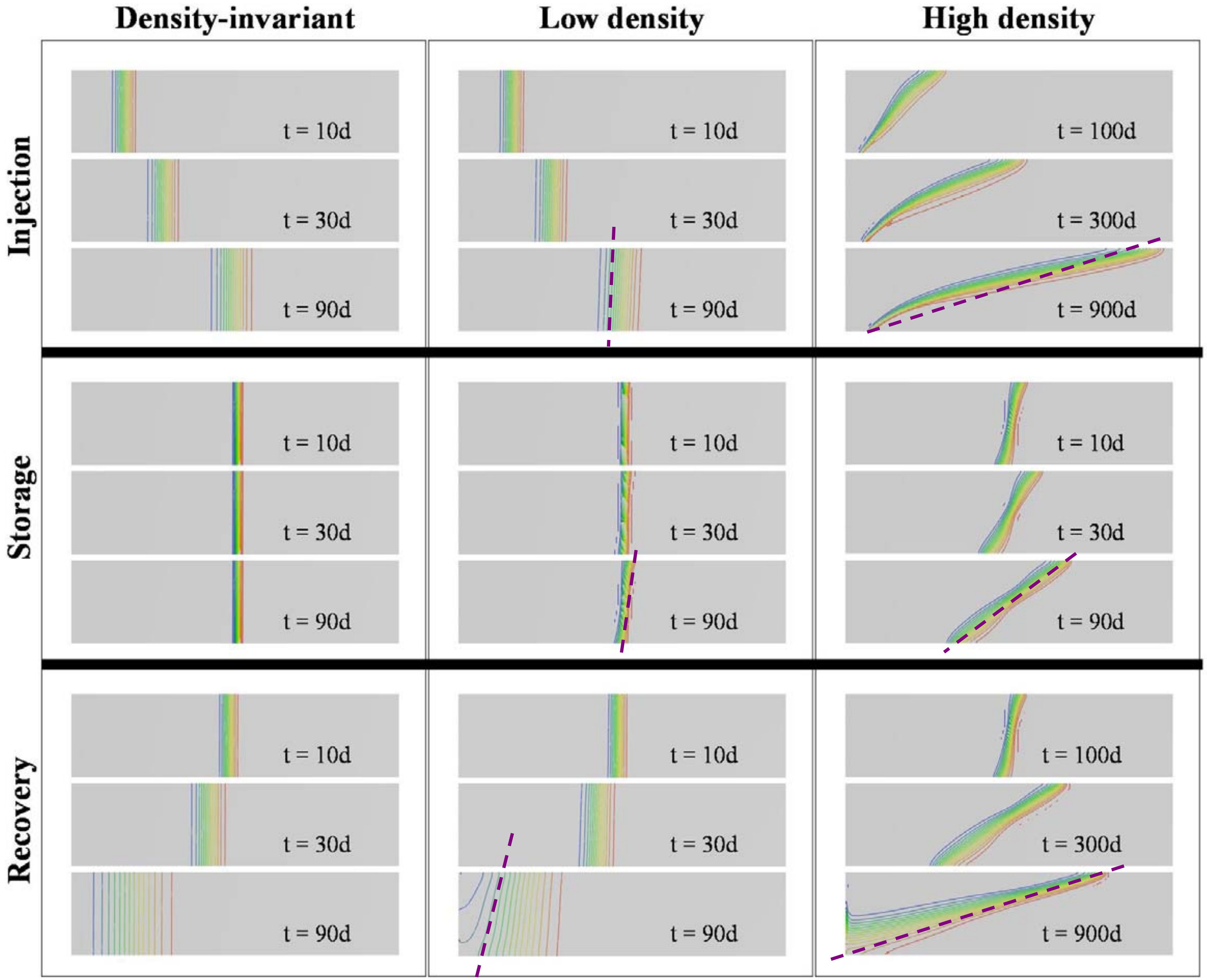


Expectations (2)

- Combination of injection rate and density contrast such that M ≥ 1
  - Mixed convective regime



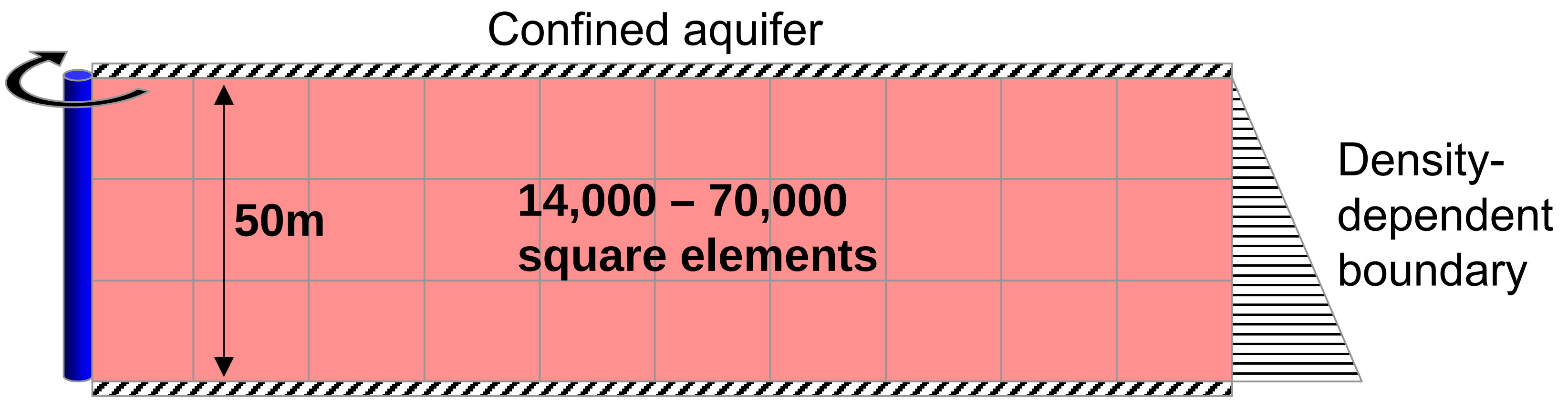
Qualitative model results



Numerical model (FEFLOW)

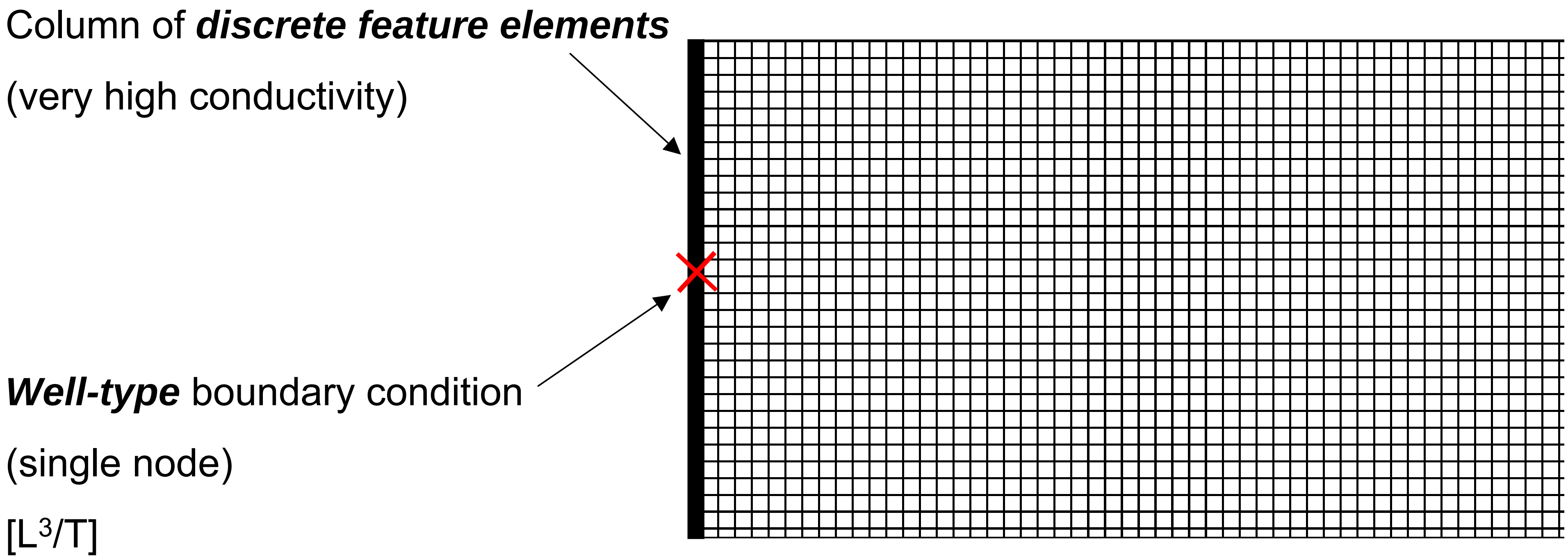
- Isotropic, homogeneous aquifer
- Axisymmetric (no background flow)

BASIC MODEL:



Simulating a well with density

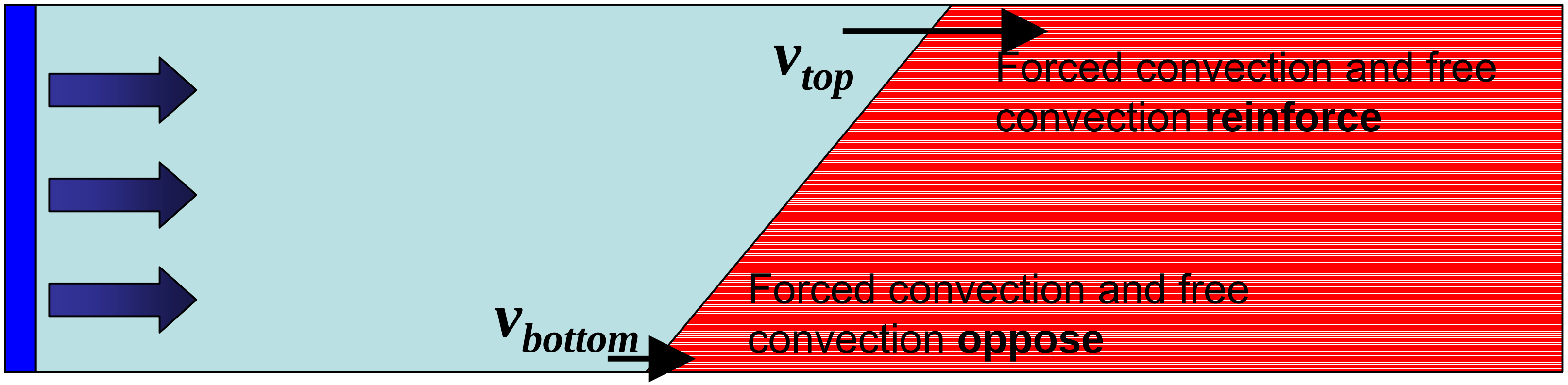
- Potential for non-uniform velocity field (can't simply use uniform flux)



Measuring mixed convection

- During injection / recovery
- "Velocity ratio"

$$\frac{v_{bottom}}{v_{top}} \quad \text{(injection)} \qquad \frac{v_{top}}{v_{bottom}} \quad \text{(recovery)}$$



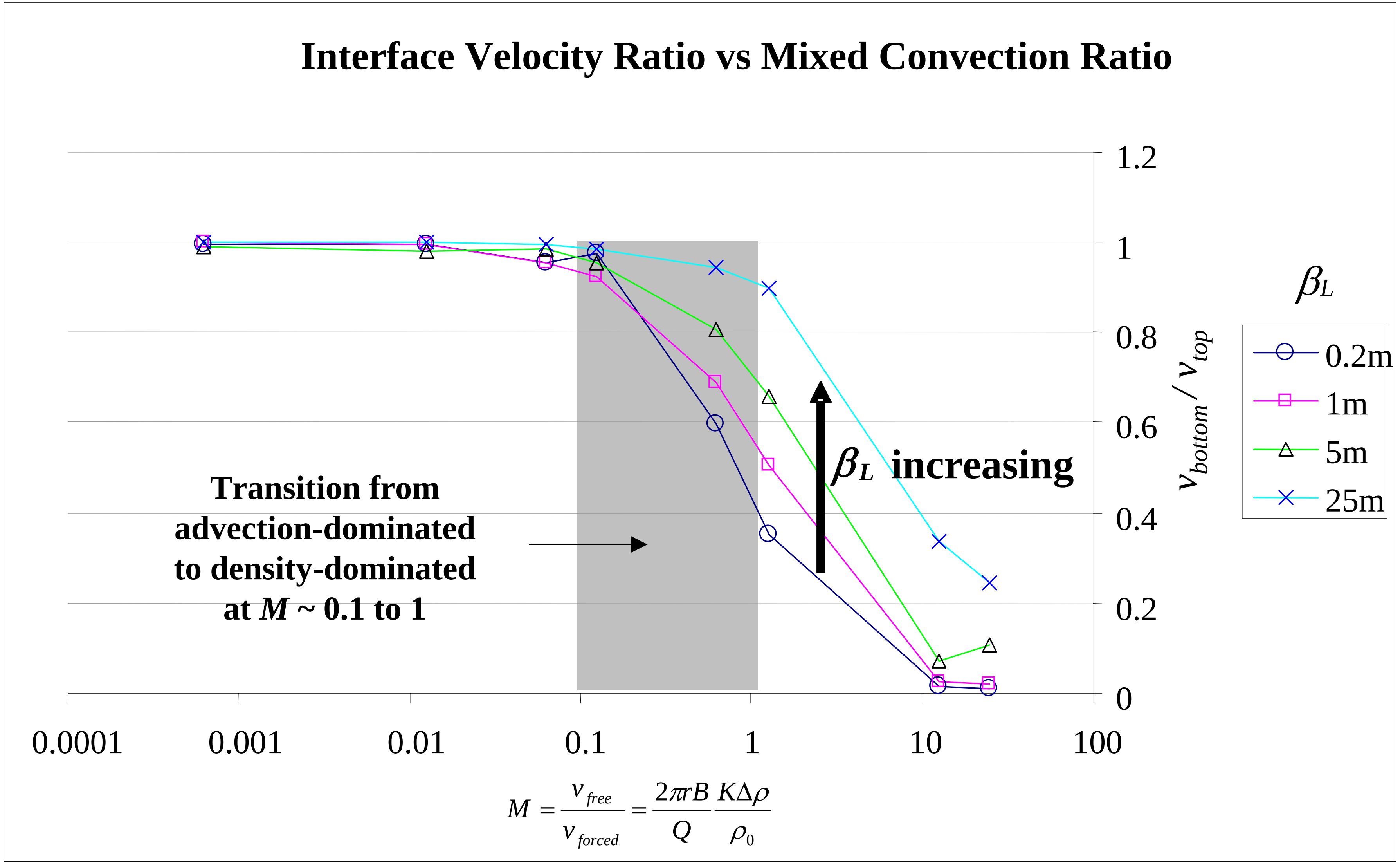
Expectation:
= 1 for forced convection dominated
= 0 for stagnation at bottom/top of interface

(Velocity taken to be time rate of change of interface position)

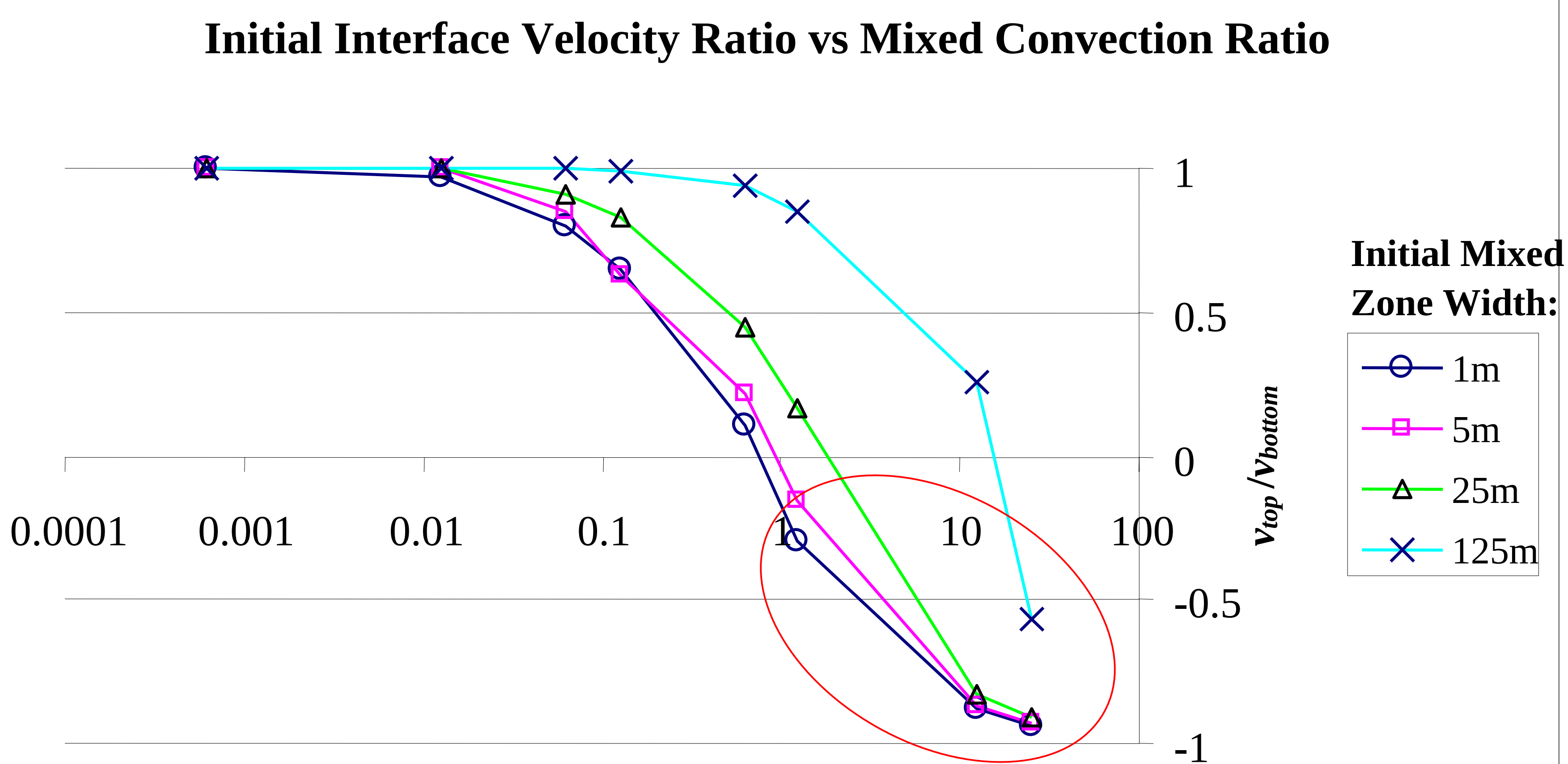
Model Parameters

- *Pumping rates:*
  500 – 5,000 m³/d
- *Ambient concentration:*
  2,000 – 20,000 mg/L
- *Hydraulic conductivity:*
  0.1 – 10 m/d
- *Injected bubble radius:*
  100 – 200 m

Results – Mixed convection during injection



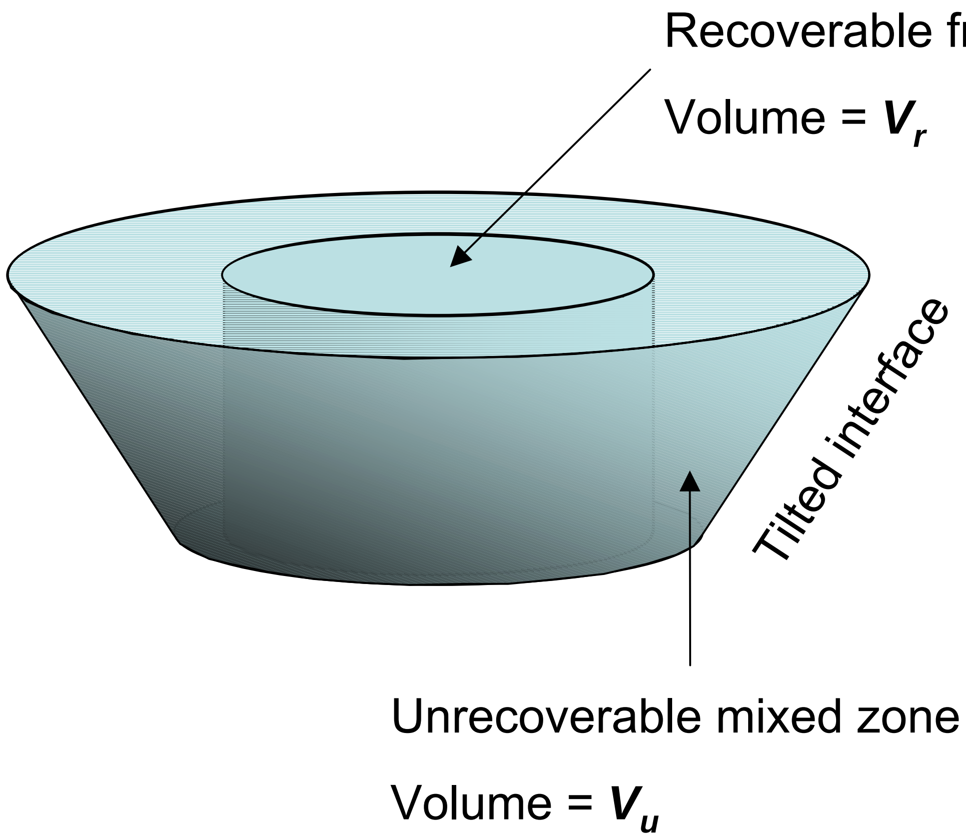
Results – Mixed convection during recovery



$$M = \frac{v_{free}}{v_{forced}} = \frac{2\pi rB}{Q}\frac{K\Delta\rho}{\rho_0}$$

Recoverability Ratio *R**

- Measure of how much water has been ‘lost’ (mixing + density effects)

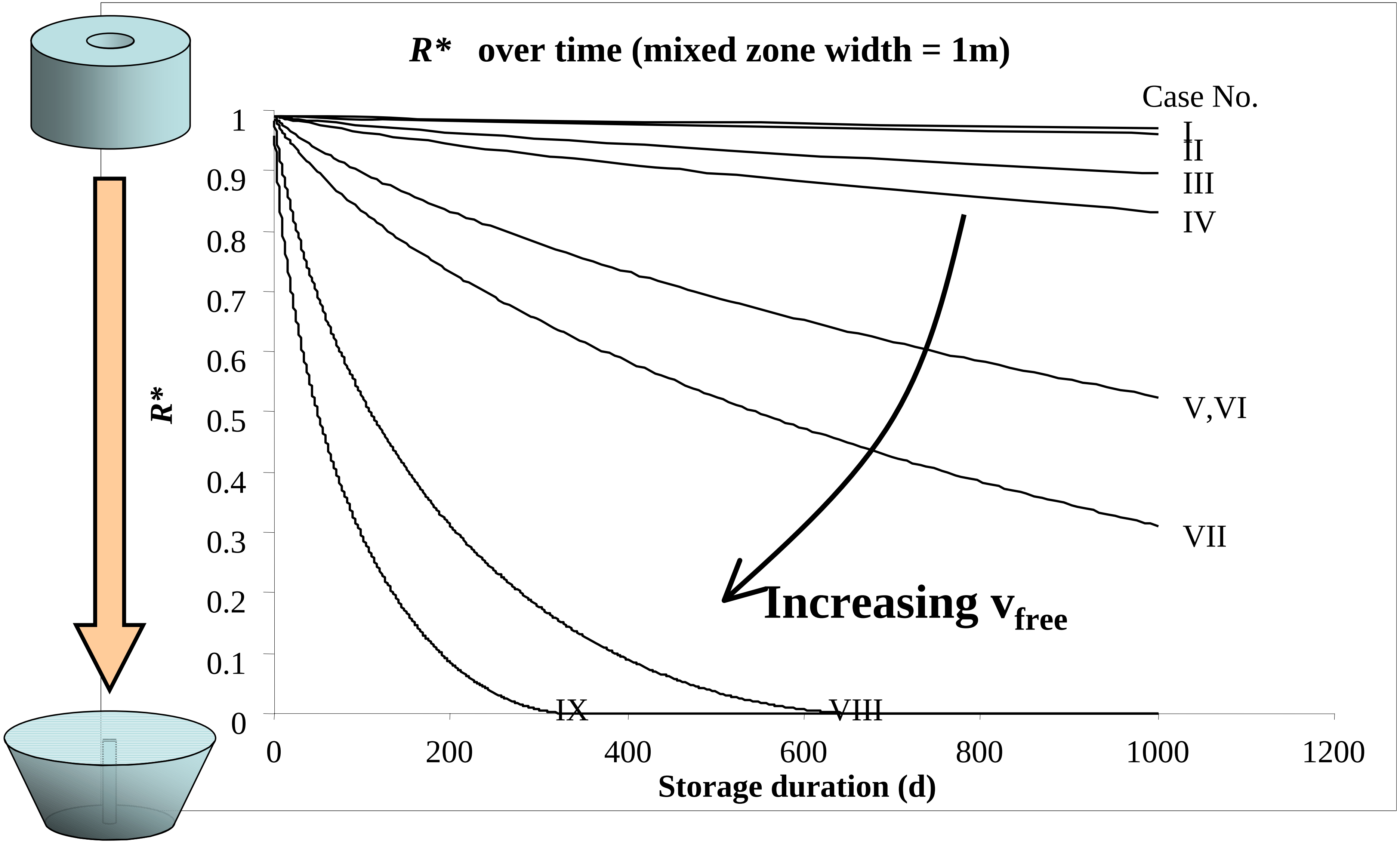


$$R^* = \frac{V_r}{V_r + V_u}$$

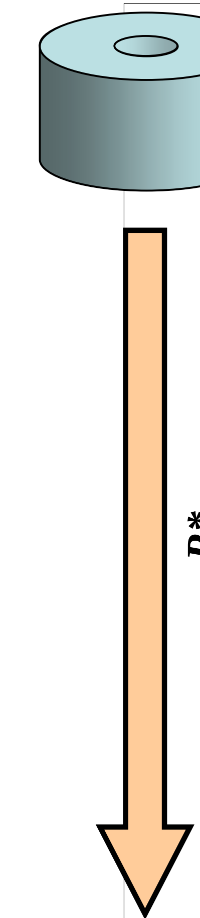
R* **low for wide mixed zone and/or severely tilted interface**

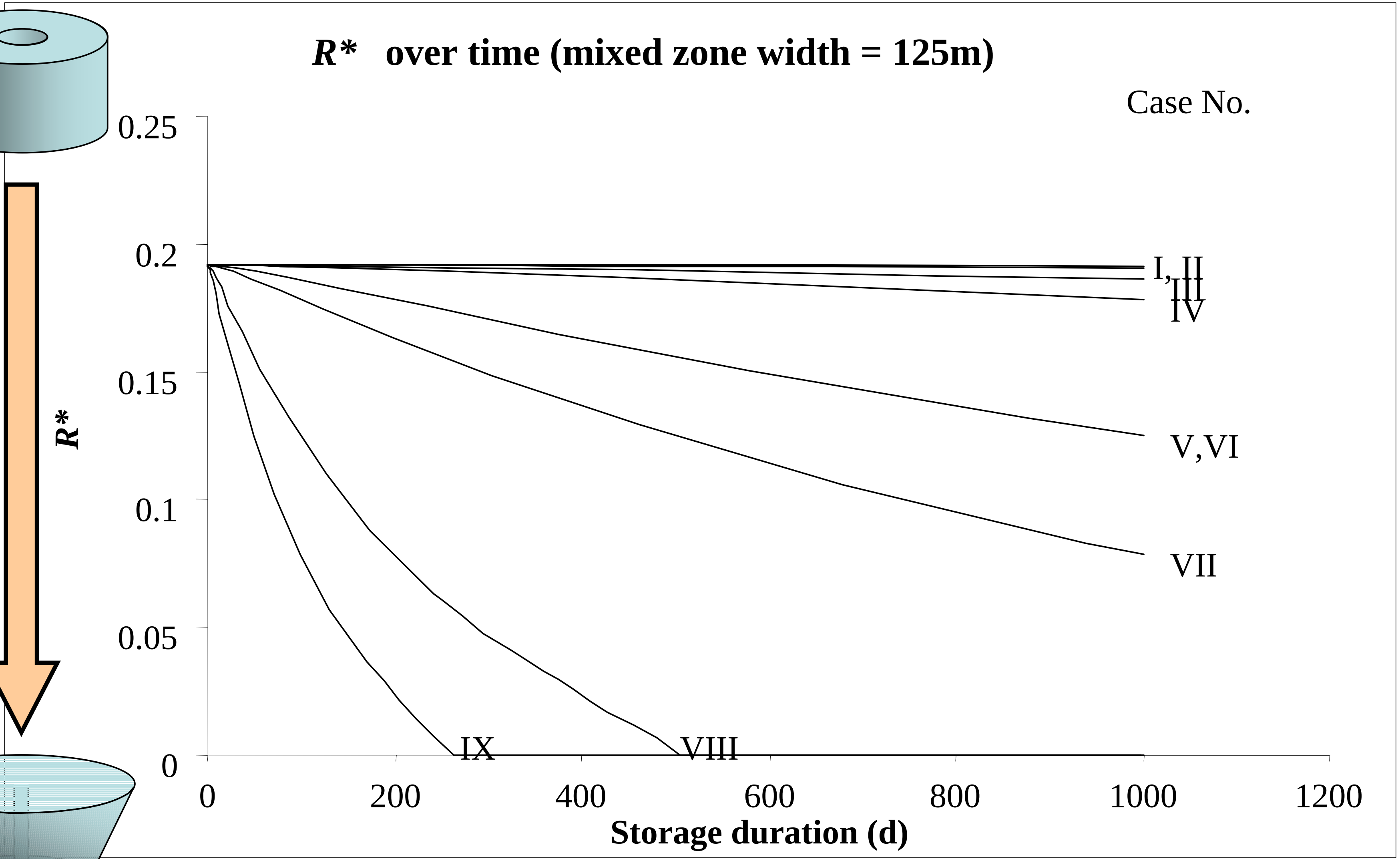
R* **high for narrow mixed zone and minimal interface tilt**

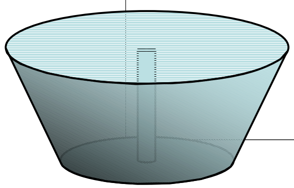
R* – storage phase



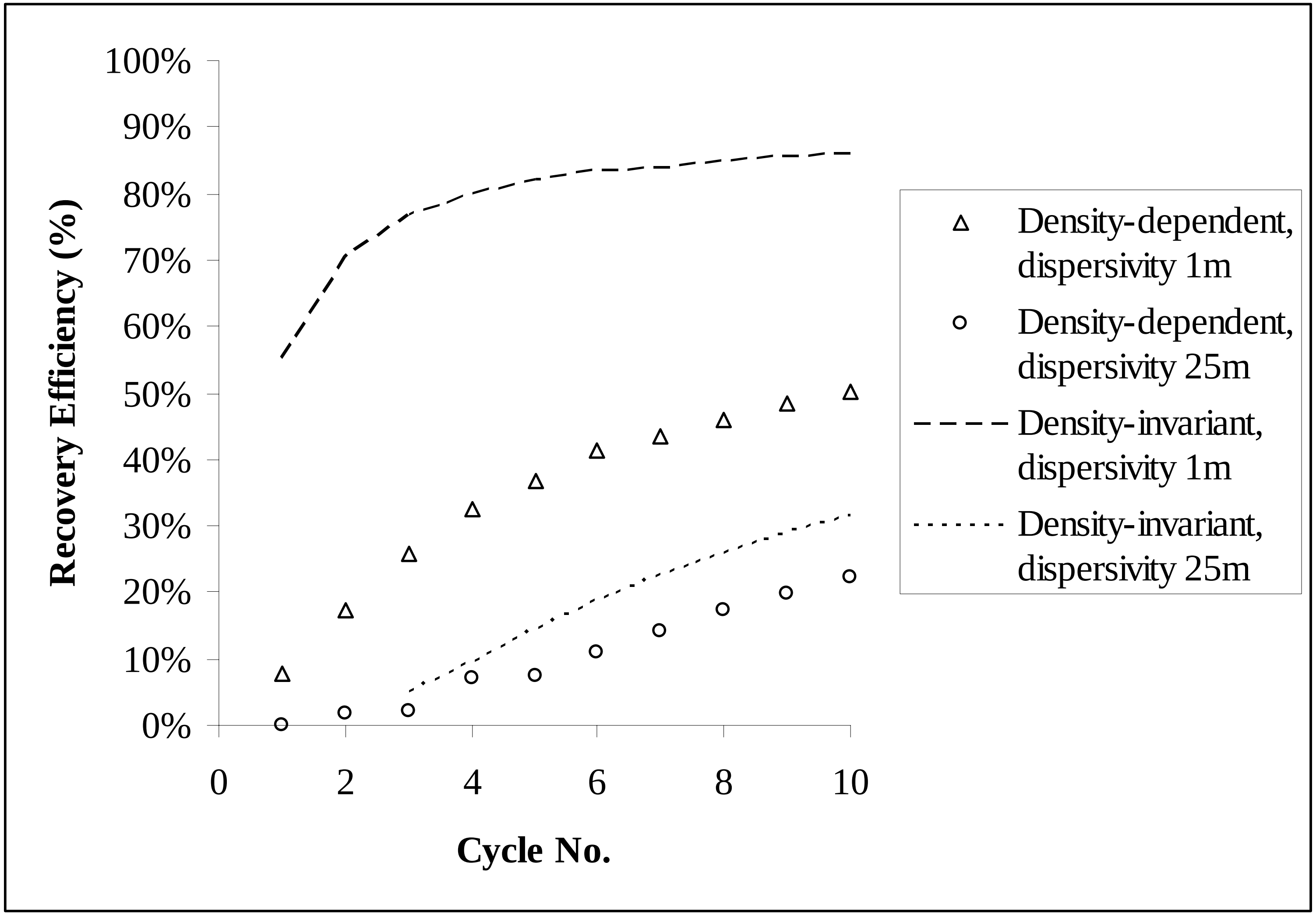
R* – storage phase (wide mixed zone)







A multiple cycle simulation



Conclusions

- M ratio useful for characterising behaviour during injection & recovery
- V ratio useful for measuring mixed convection
- Cannot claim density effects are “negligible” based purely on concentration difference
  - Slow pumping
  - High hydraulic conductivity
  - Long storage durations

} ***Could all lead to density effects in cases where ΔC is small***

Where to from here?

- More realistic modelling scenarios
  - Anisotropy
  - Layered heterogeneity } *is M still useful?*
  - Regional hydraulic gradient (3D modelling required)
- Real-world data
  - Case studies
  - What field data is needed to verify simulation?