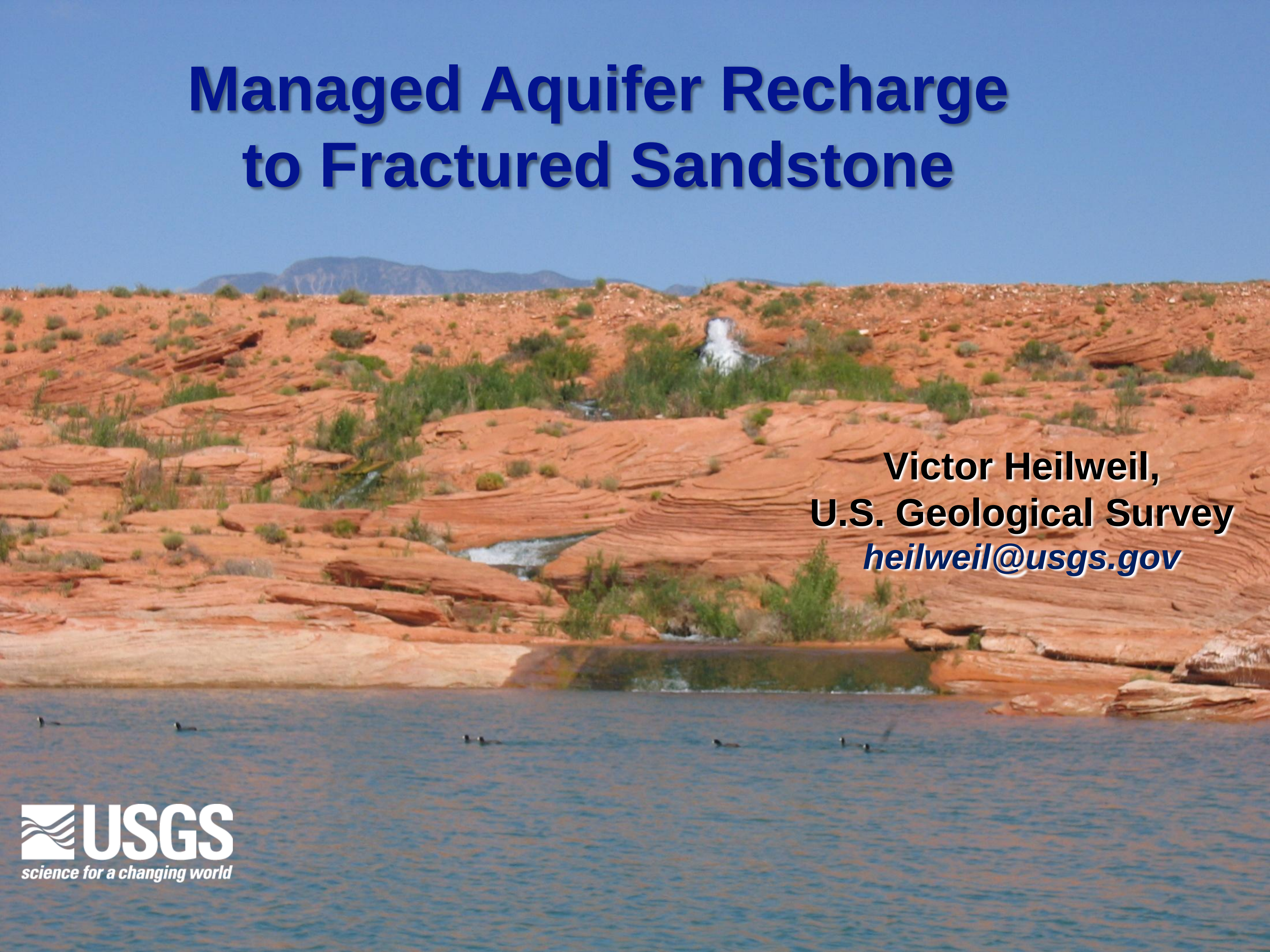
# Managed Aquifer Recharge to Fractured Sandstone



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USGS
science for a changing world

# Rationale

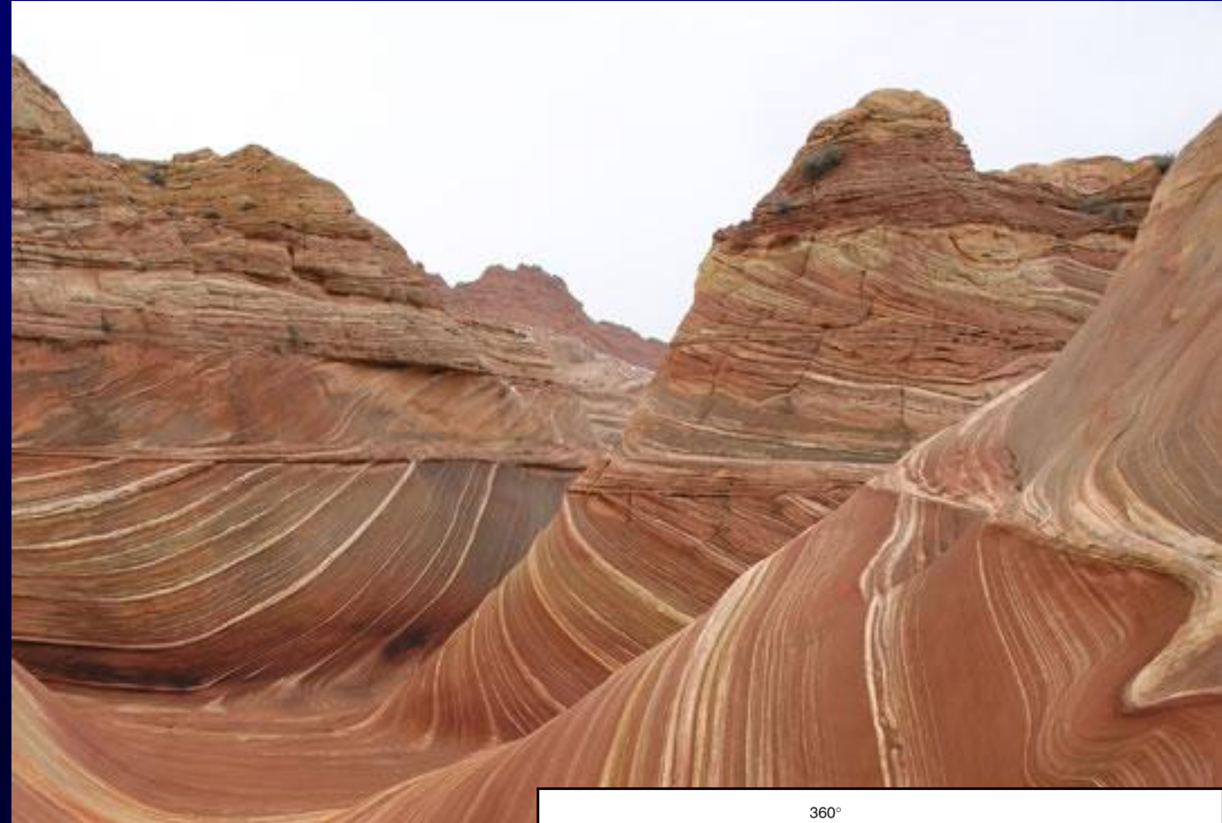
- Sandstone aquifers provide water to tens of millions of people worldwide
- In arid regions, sustainable groundwater management increasingly utilizing bedrock Managed Aquifer Recharge (MAR) to offset groundwater exploitation
- In Colorado River Basin, alternative to surface-water storage

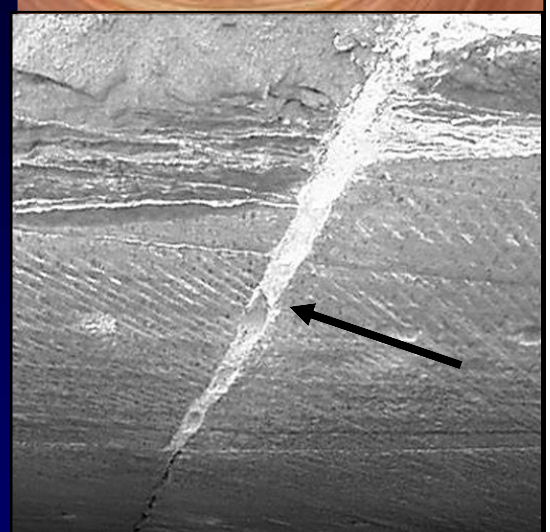
## Navajo Sandstone

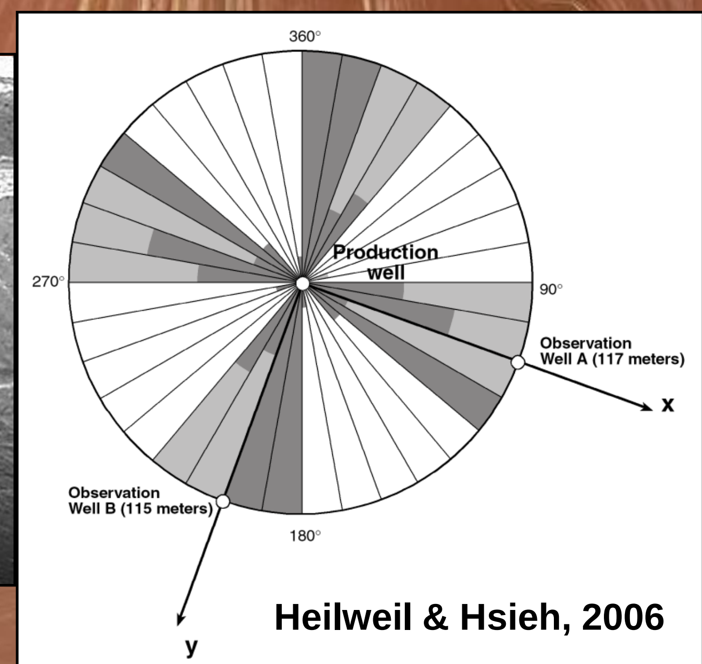
- Well-sorted eolian fine sand and $CaCO_3$ cement
- Porosity ~ 20 %
- Hydraulic conductivity 0.1 – 3 m/d
- Fracture anisotropy up to 30:1

## Caliche Deposits

- Root transpiration
- Hydraulic conductivity 0.0001 – 0.01 m/d








Heilweil & Hsieh, 2006


## Navajo Sandstone

- Total thickness up to 1,000 m
- Forms exquisite cliffs in many National Parks and Monuments of the Colorado Plateau:

Zion, Glen Canyon, Canyonlands, Pipe Springs, Natural Bridges

# Navajo Sandstone

- The 2nd largest eolian sandstone in western hemisphere, covering 600,000 km$^2$ in Colorado Plateau
- Bisected by the Colorado River

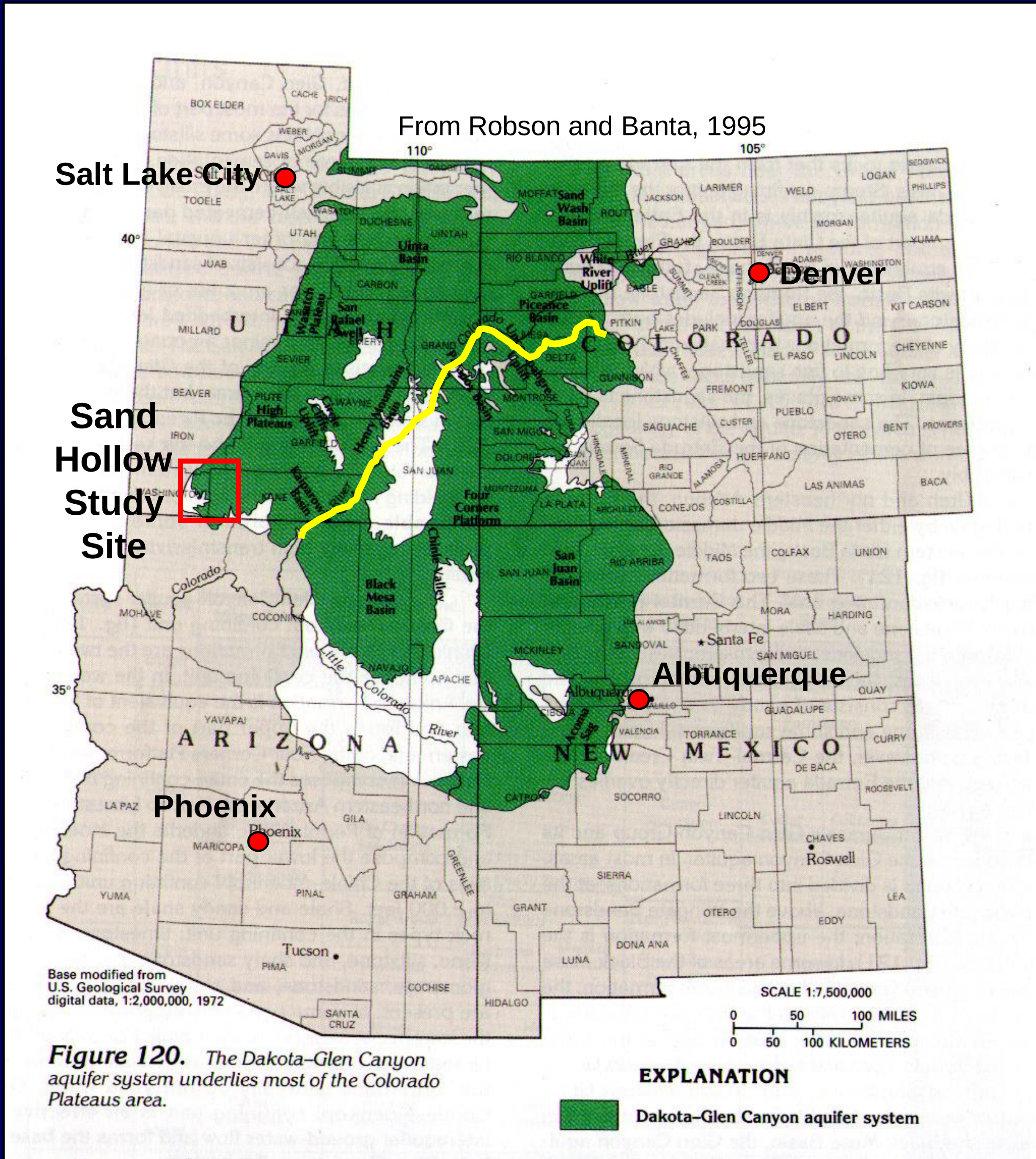
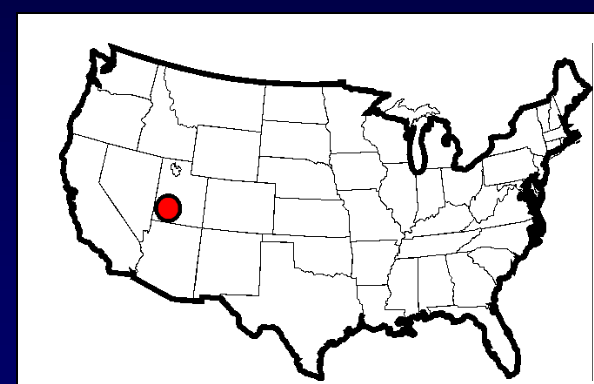
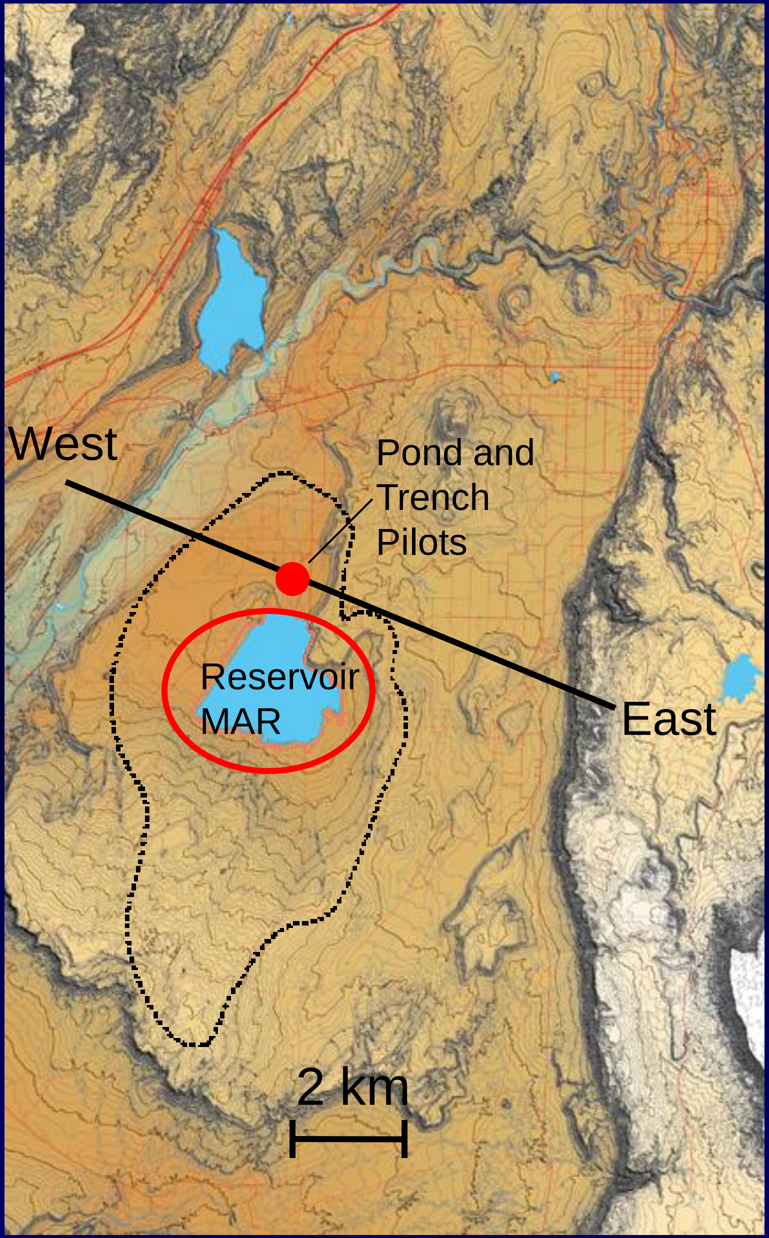


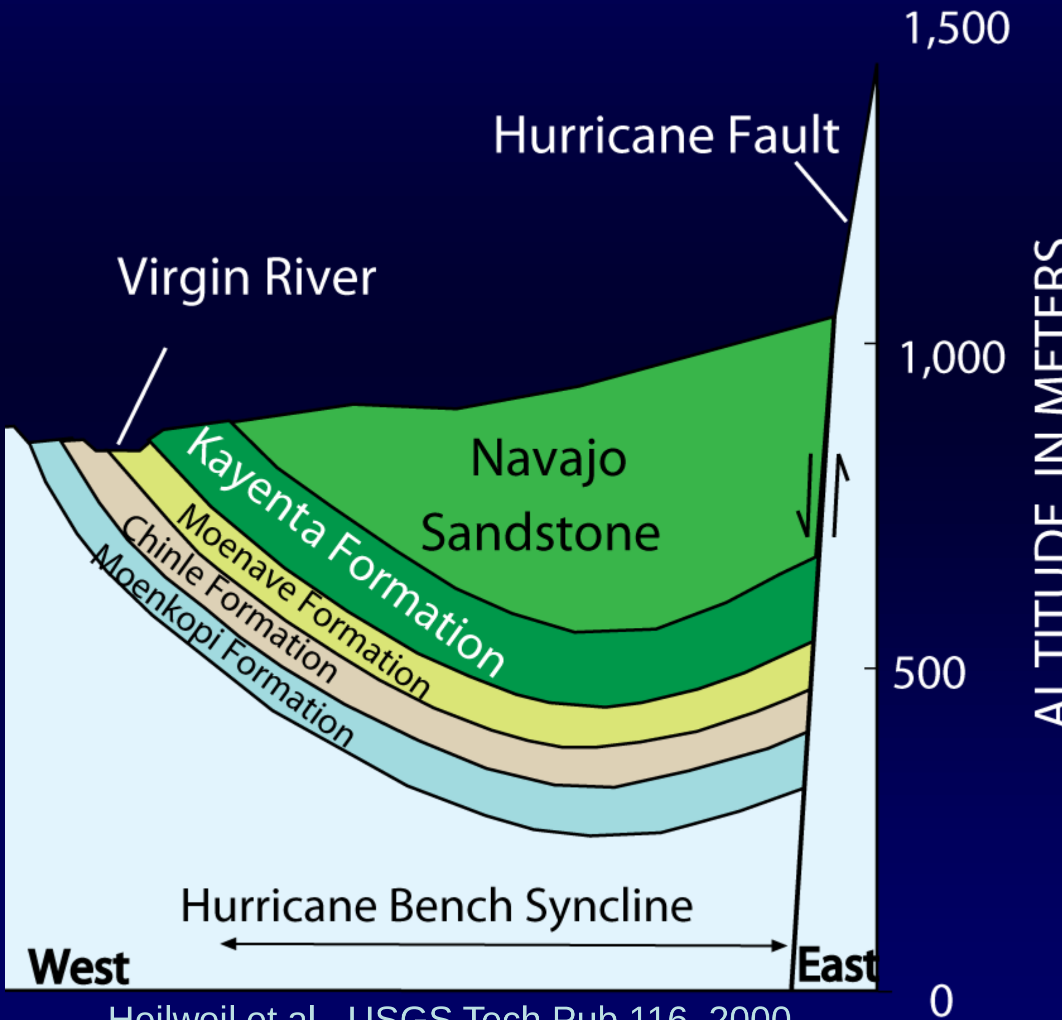

*Figure 120.* The Dakota–Glen Canyon aquifer system underlies most of the Colorado Plateaus area.



# Managed Aquifer Recharge Studies at Sand Hollow




- Reservoir MAR
- Trench and Pond Pilots



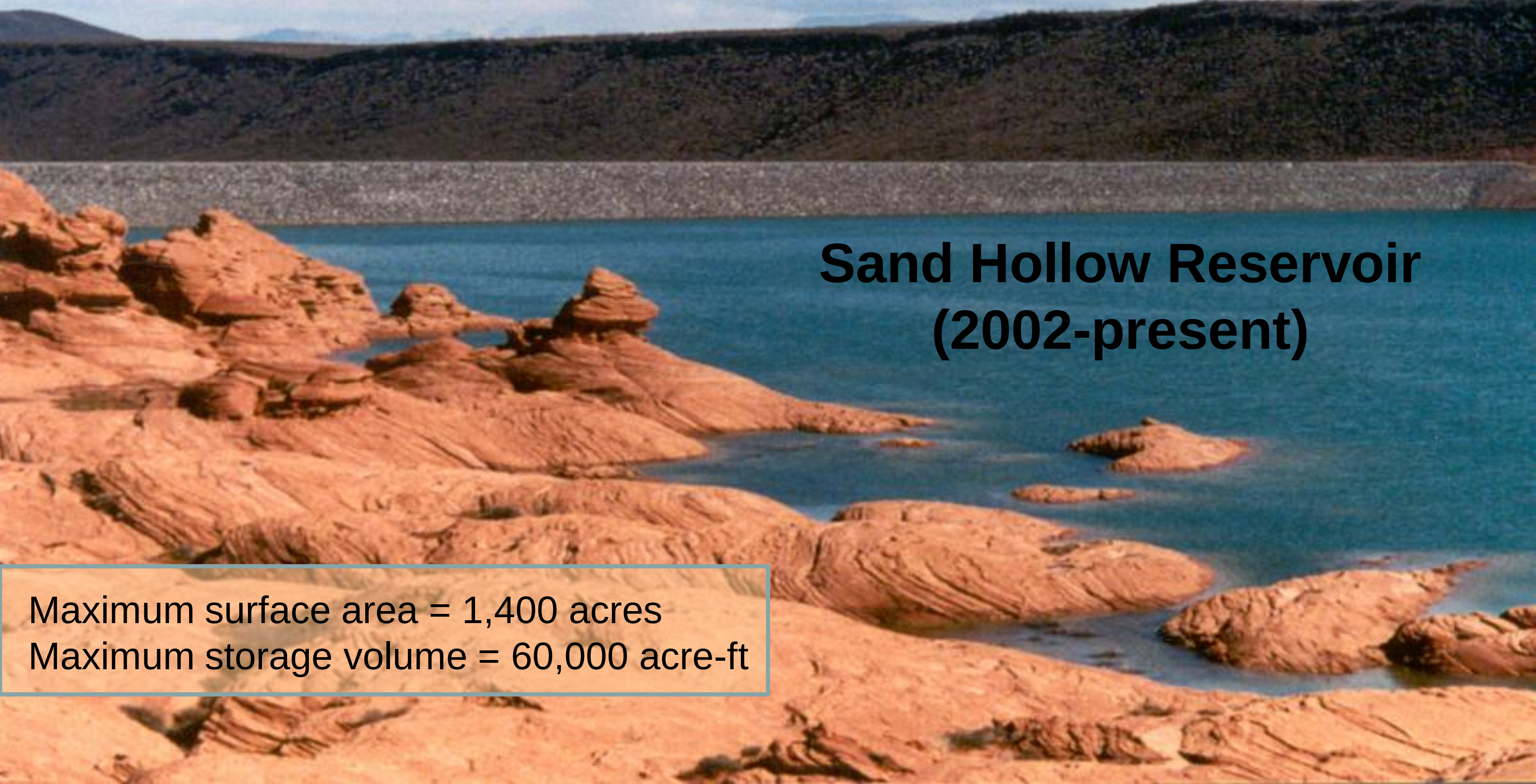

Heilweil et al., USGS Tech Pub 116, 2000

# Talk Outline:

(A) Processes controlling recharge rates

(B) Technique to maximize recharge

(C) Evaluation of groundwater residence times



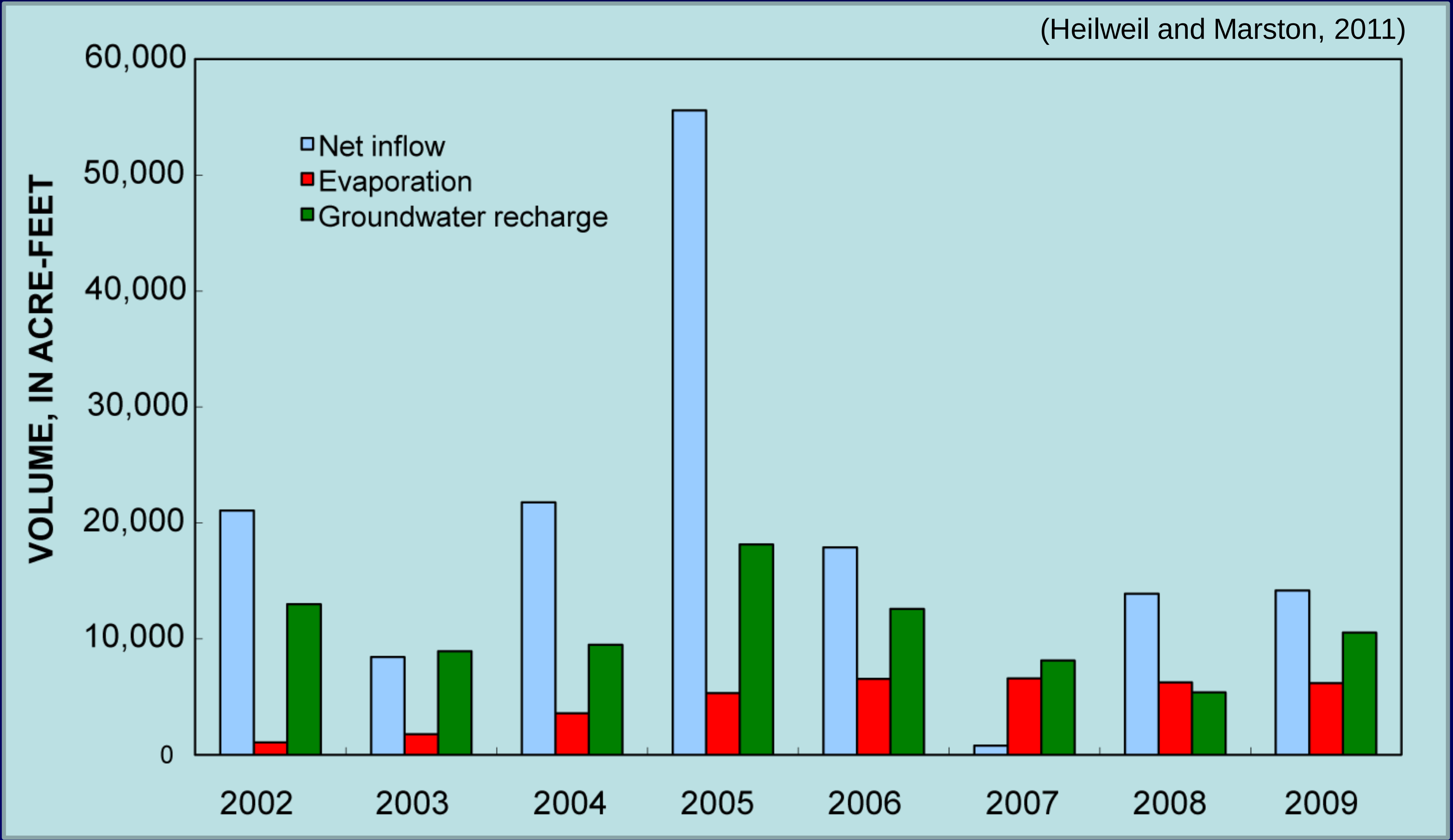
# Recharge Determined from Water Budget

$$\textbf{Recharge} = I_{sw} + P - O_{sw} \pm \Delta S - E$$

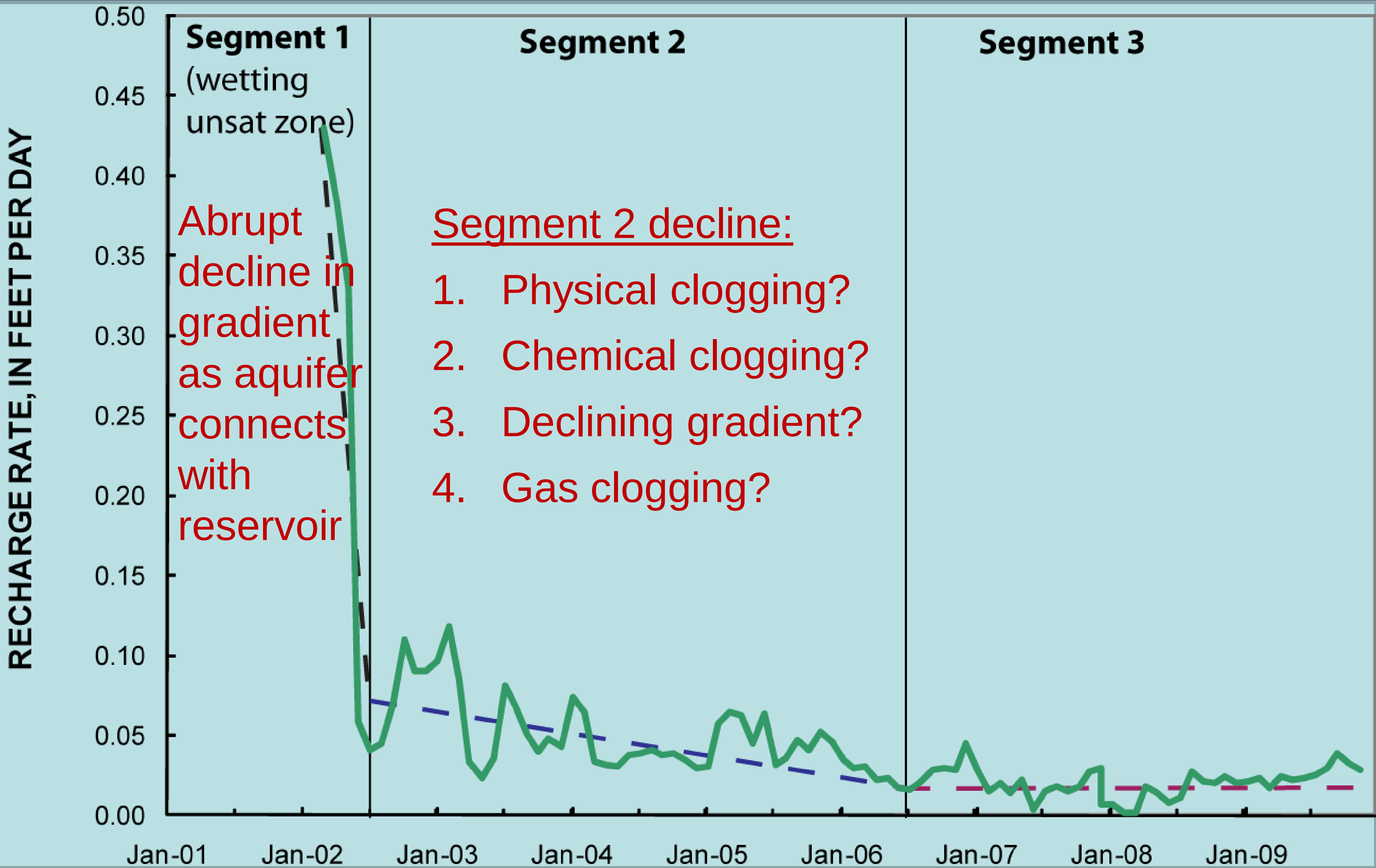
E determined using Jensen–Haise Method:
Function of temperature and solar radiation

## 2002-2009 Totals

Inflow = 154,000 acre-ft
Evaporation = 37,000 acre-ft
Recharge = 86,000 acre-ft



# After initial wetting up, recharge rates from 2002 - 2006 generally declined

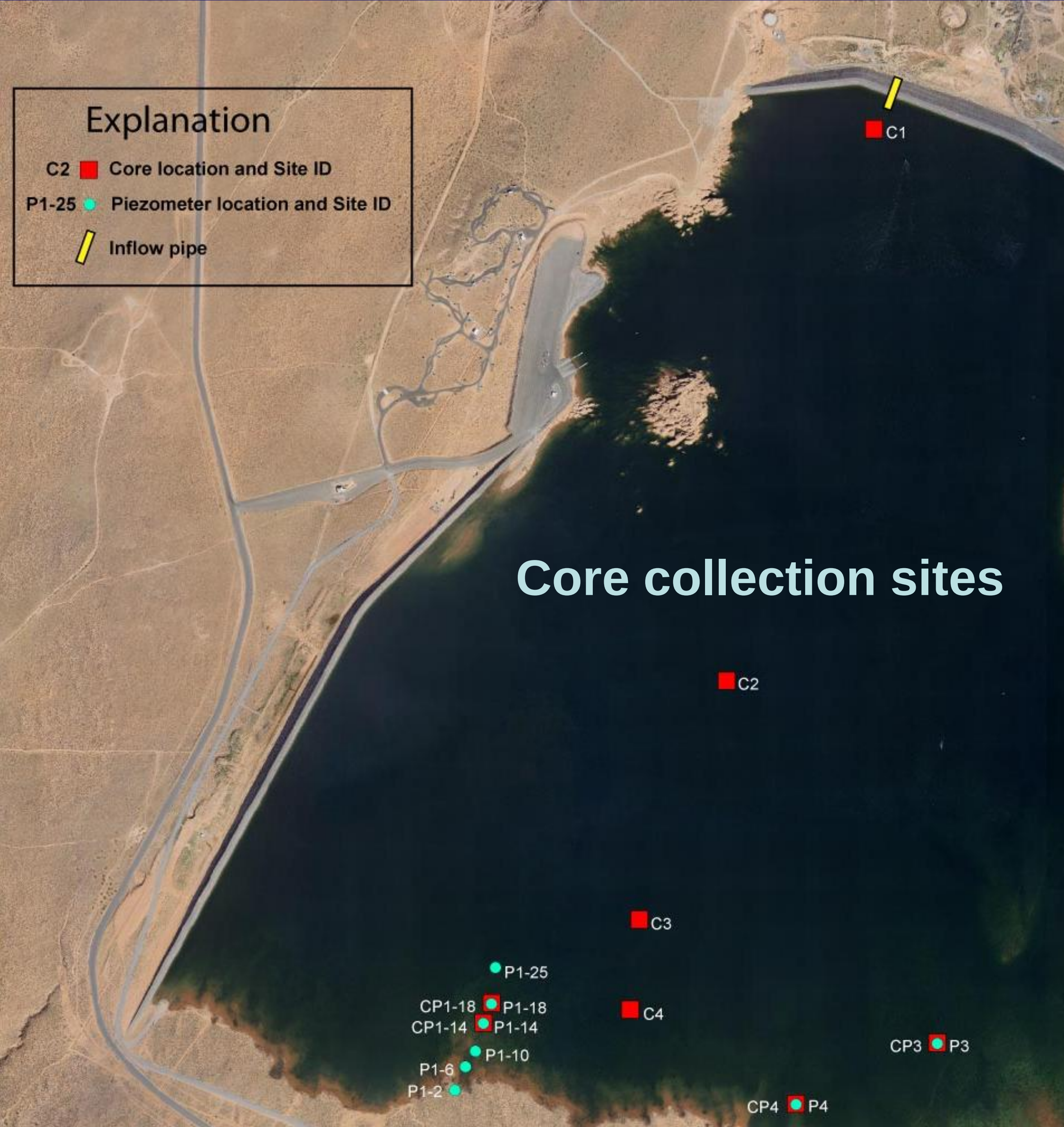


# 1. Evaluation of physical clogging from siltation

- Sediment core sample collection at 8 sites beneath Sand Hollow Reservoir (2 to 20 m water depth)
- 2002-2008 silt accumulation of 8 to 23 cm (Heilweil, Solomon, Ortiz, 2009)
- Most permeability reduction where silt layer is thickest

*Sand Hollow core sample collection by Gema Ortiz (Instittúto Geológico y Minero de Espaňa) using a slide-hammer percussion coring device*

# Core collection sites

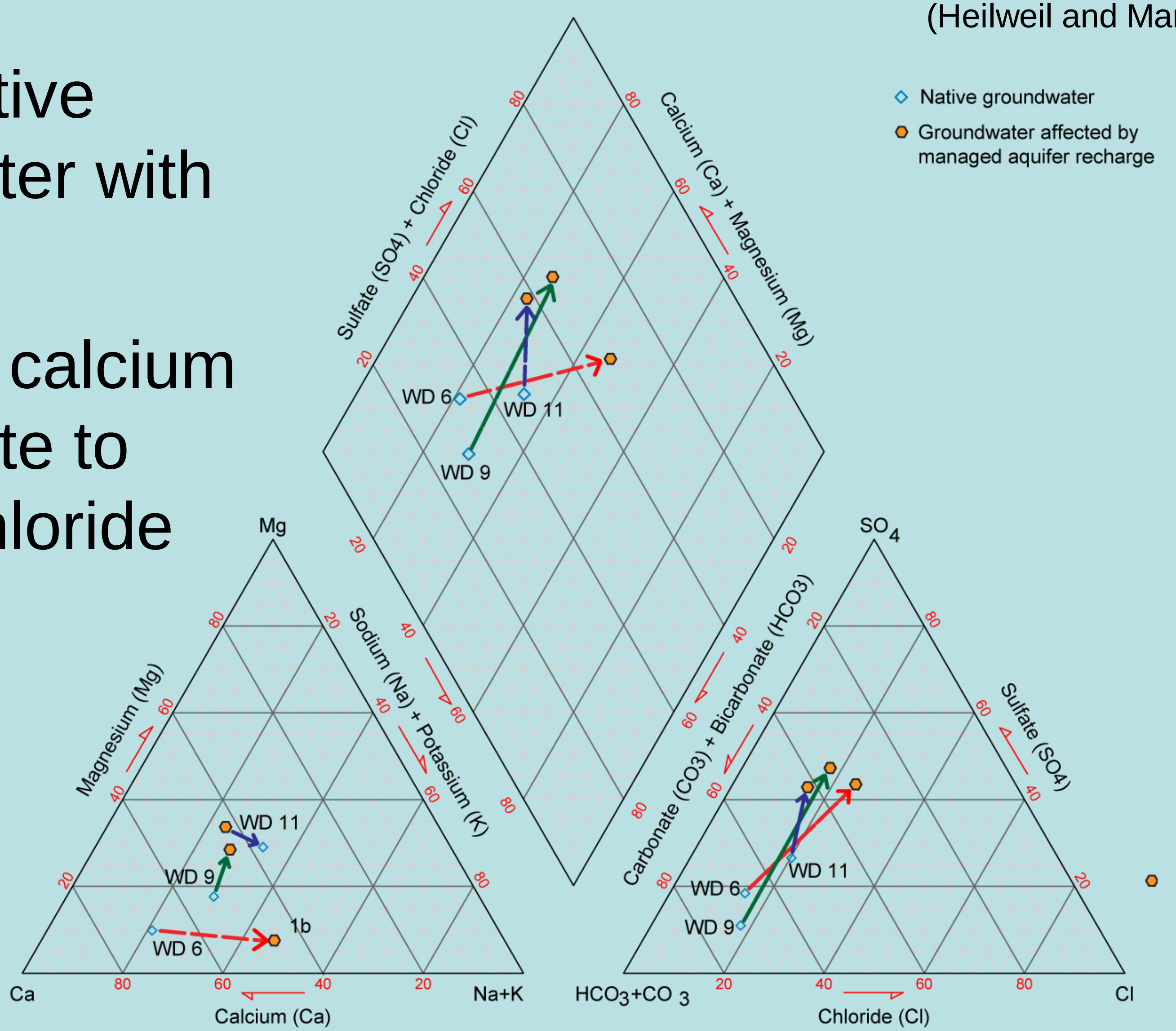



# 2. Evaluation of chemical clogging

(Heilweil and Marston, 2011)

Mixing native groundwater with MAR

Shift from calcium bicarbonate to sodium chloride



# PHREEQC modeling of groundwater/surface water mixing:

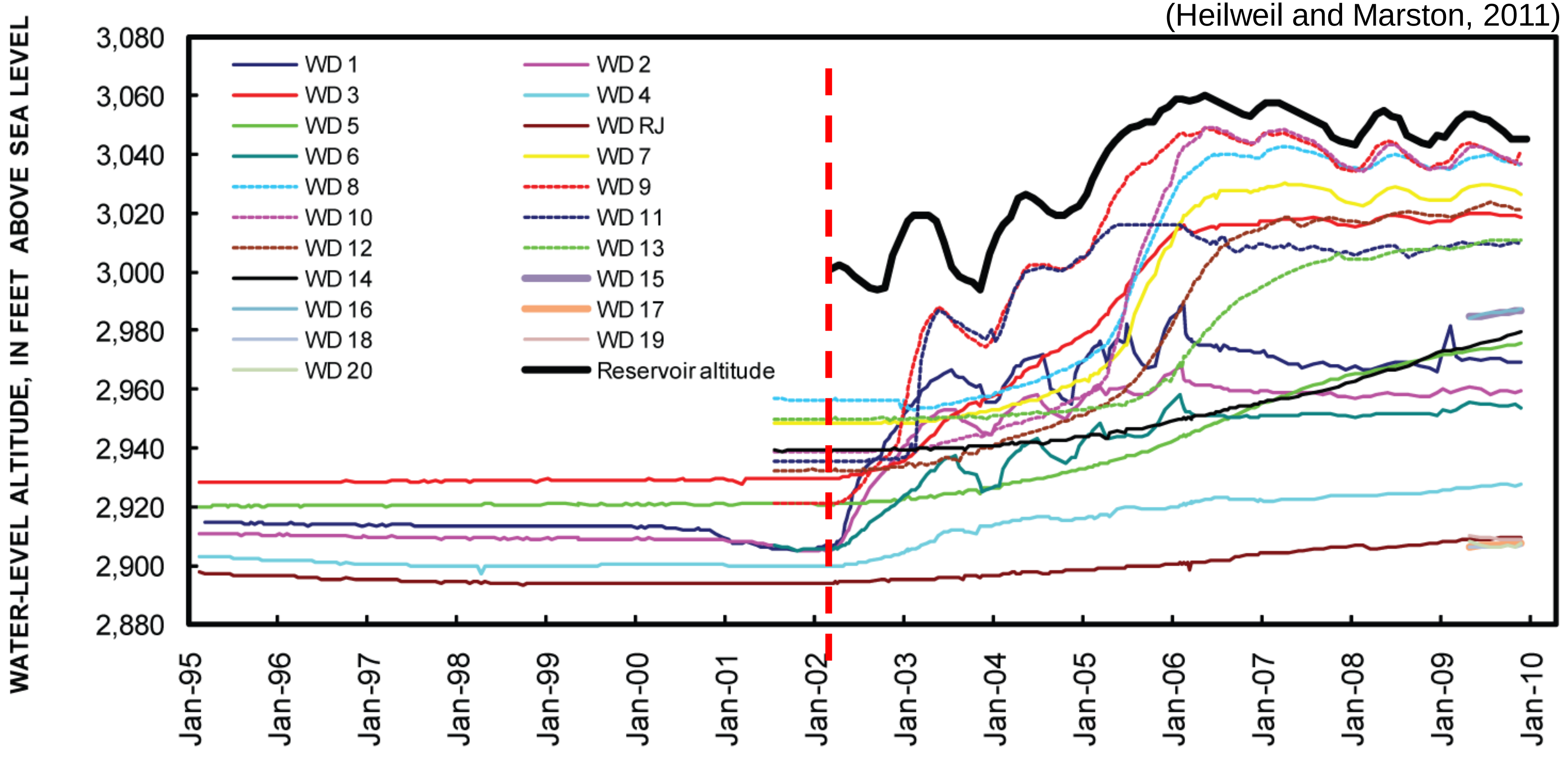
- Mixing MAR with groundwater will cause some precipitation of trace amounts of iron and manganese oxides

*Collaboration with Rut Sanchez (Institúto Geológico y Minero de Espaňa)*

# 3. Evaluation of declining gradients

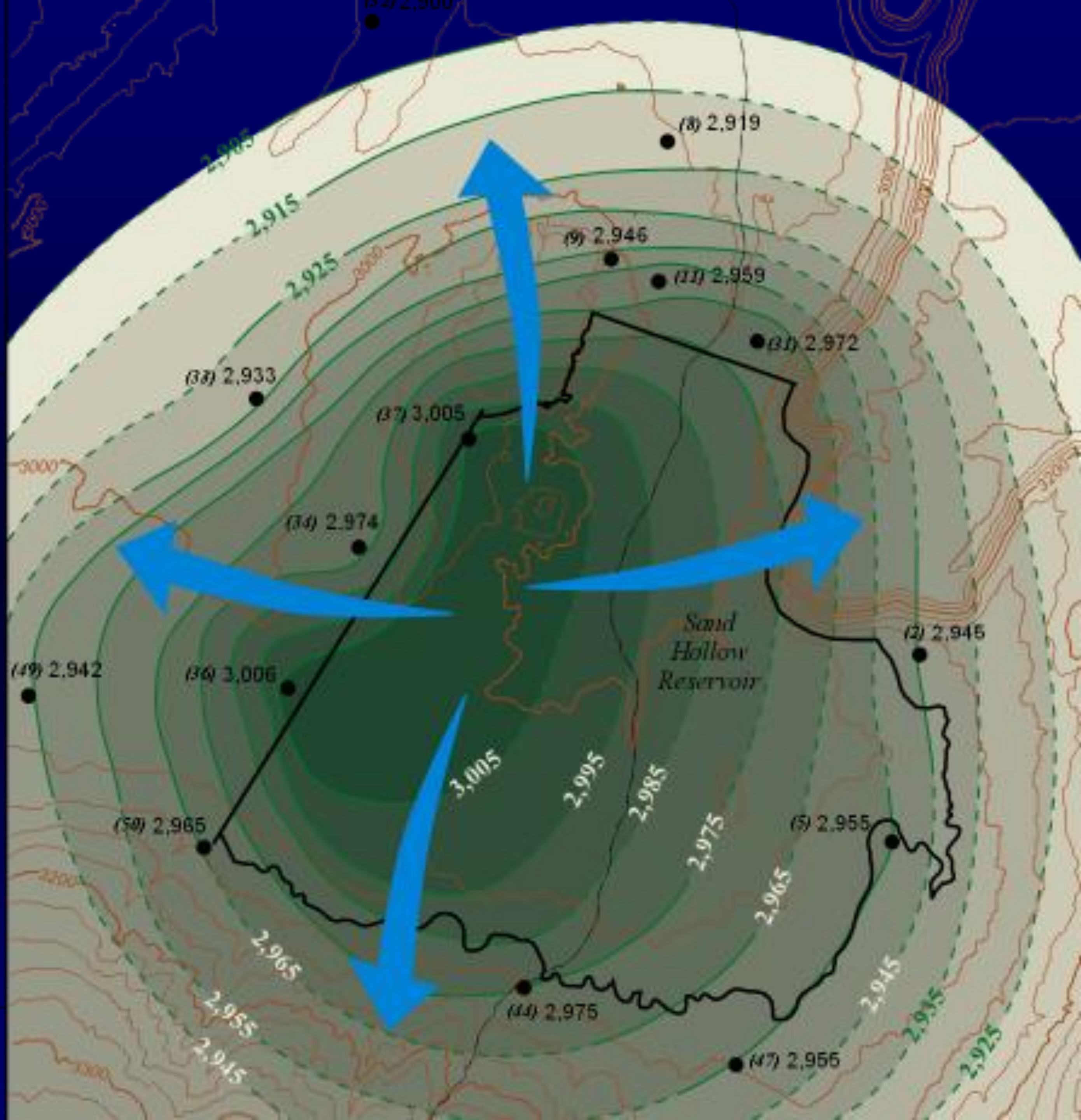
## Monthly water levels in 21 monitoring wells and reservoir altitude

(Heilweil and Marston, 2011)



## August 2004

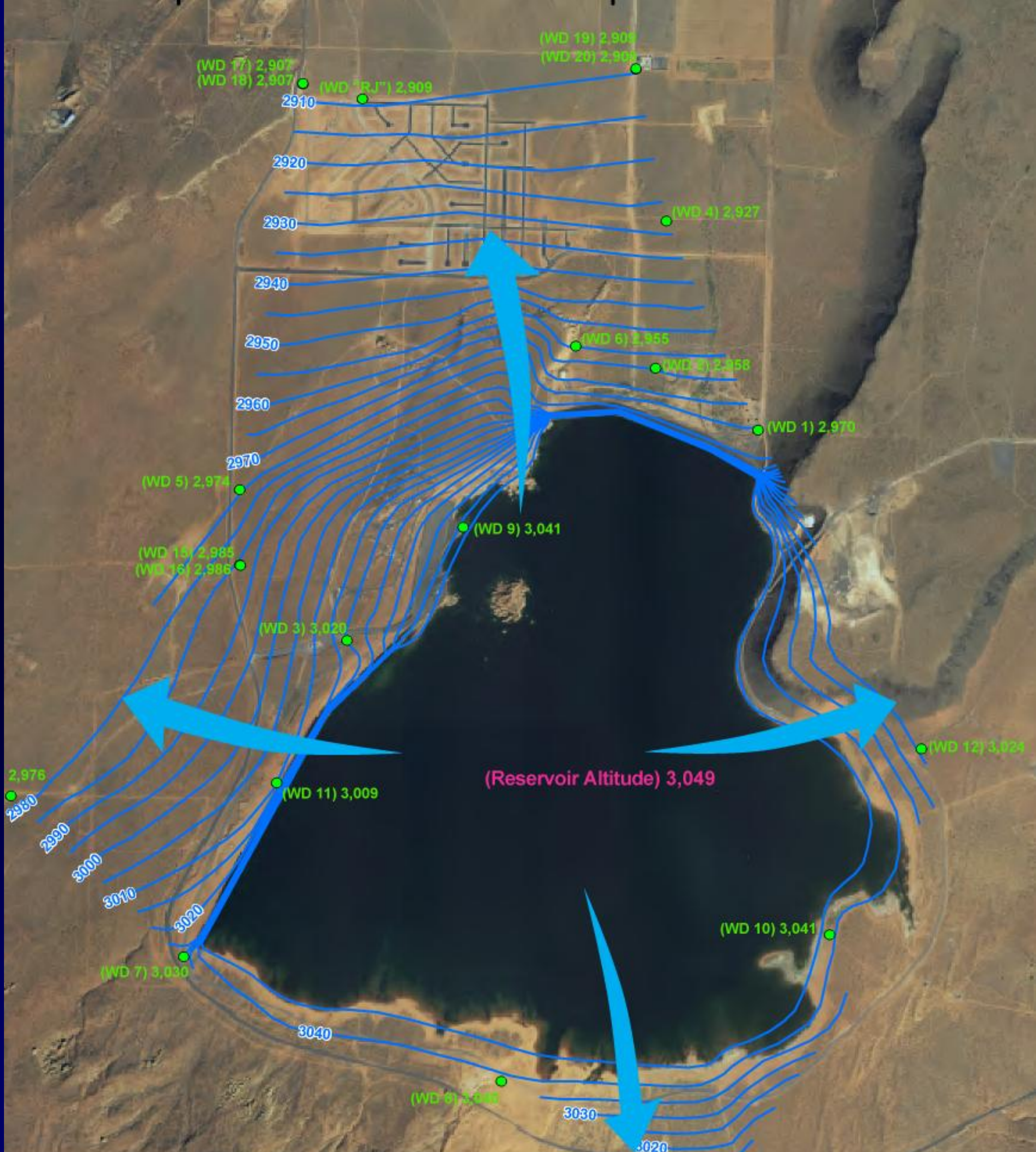
Mounding beneath Sand Hollow with steep hydraulic gradients (up to 0.10 m/m)




(Heilweil , Susong, Gardner, Watt, 2011)

August 2009

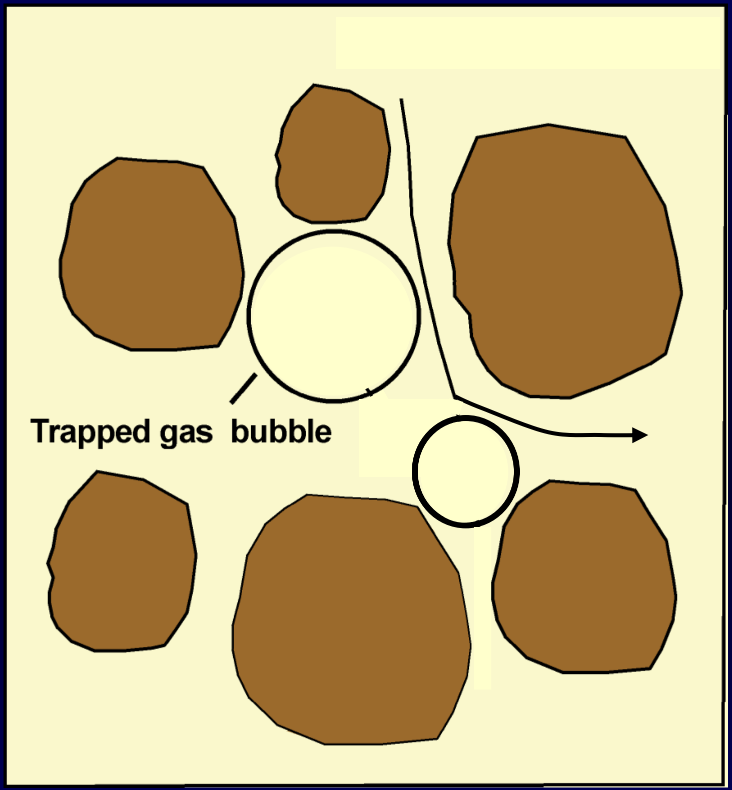
Similar hydraulic gradients near reservoir (up to 0.12 m/m)

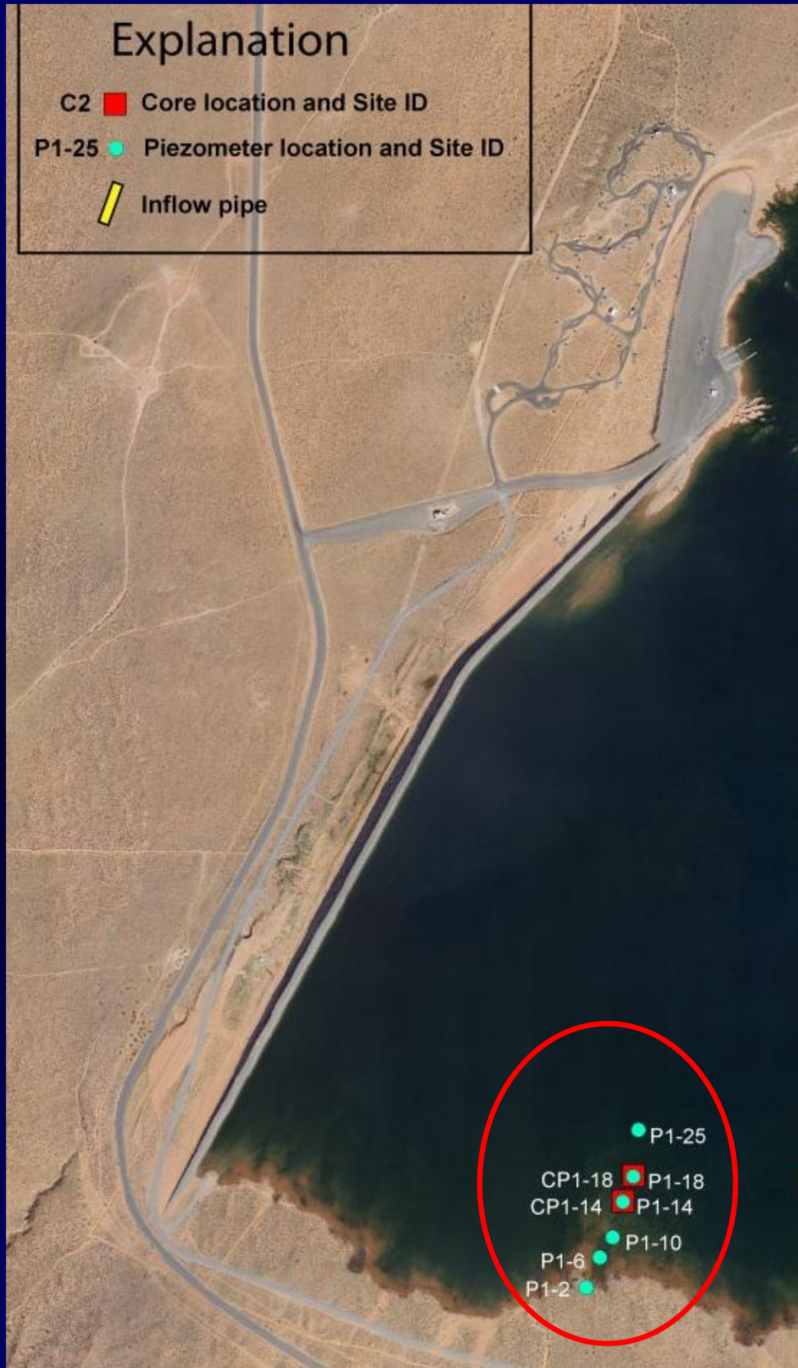



(Heilweil and Marston, 2011)

# 4. Evaluation of gas clogging

- Gas clogging shown to cause a 10-fold reduction in permeability
- In addition to trapped air, biogenic gas production can also cause clogging
- Biogenic gases are produced by plant respiration and decay





(Heilweil, Solomon, Ortiz, 2009)

## Biogenic Gases

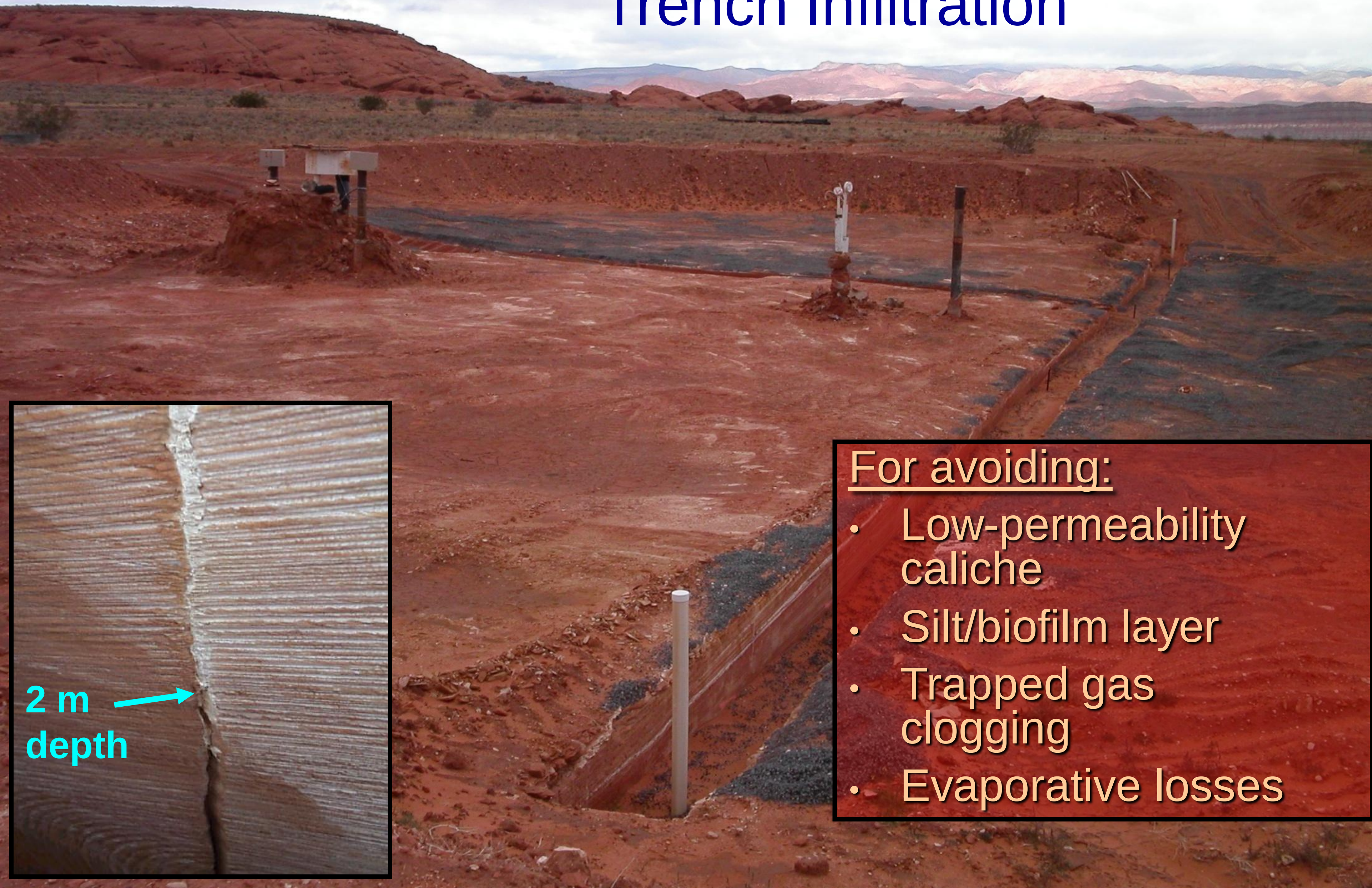
<u>Shallow piezometer gas sampling:</u>

• TDGPs higher in summer than winter, sometimes exceed hydraulic head to form bubbles which cause seasonal clogging in shallow areas

• High $CO_2$ and $CH_4$ concentrations indicate biogenic respiration and decay

•These trapped gases may explain some of the seasonal variability in recharge rates

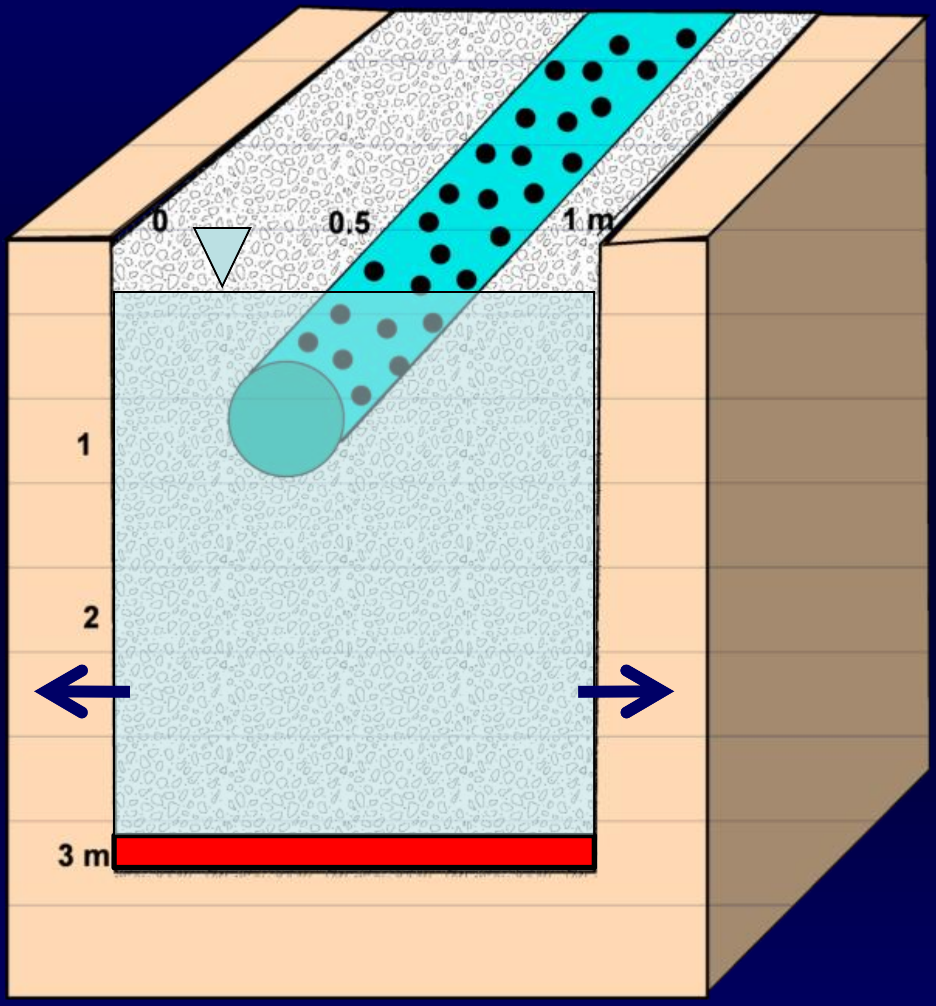
# (B)Technique to Maximize Recharge: Trench Infiltration




For avoiding:

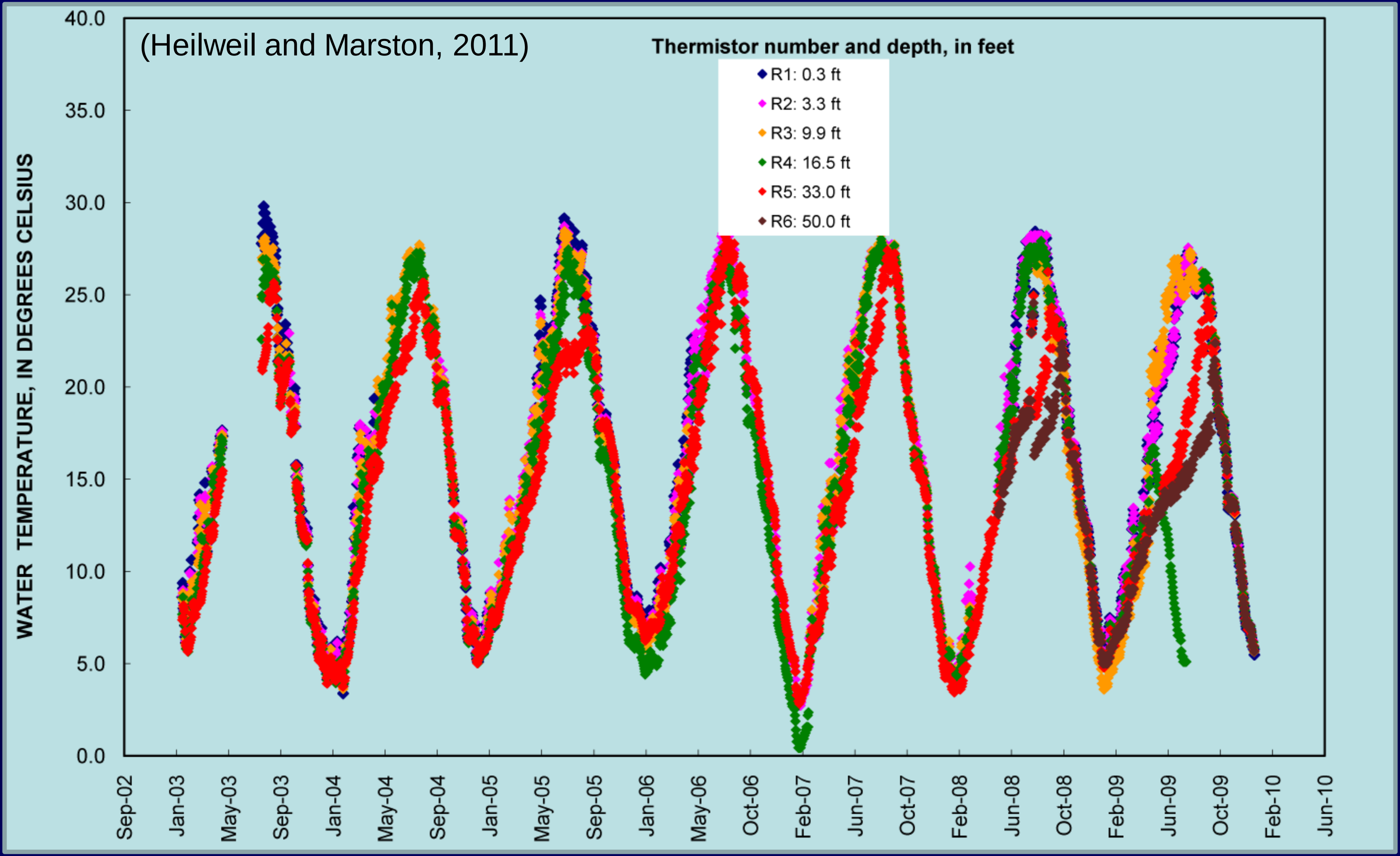
- Low-permeability caliche
- Silt/biofilm layer
- Trapped gas clogging
- Evaporative losses

Even if silt clogs trench bottom, design allows access to permeable sandstone and fractures along vertical walls



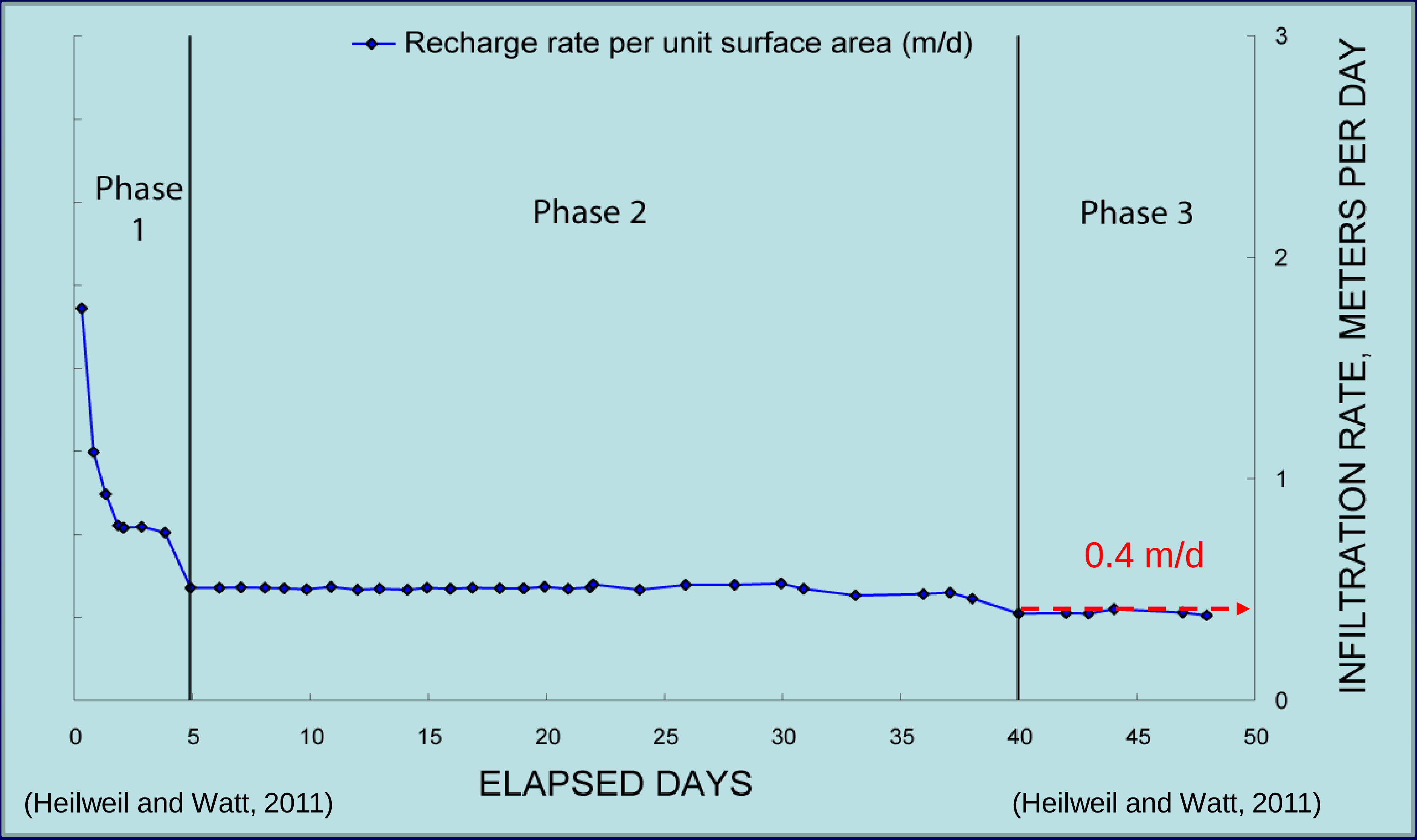

(Heilweil and Watt, 2011)

# Sand Hollow Reservoir Temperature Variation: 5 to 30˚ C

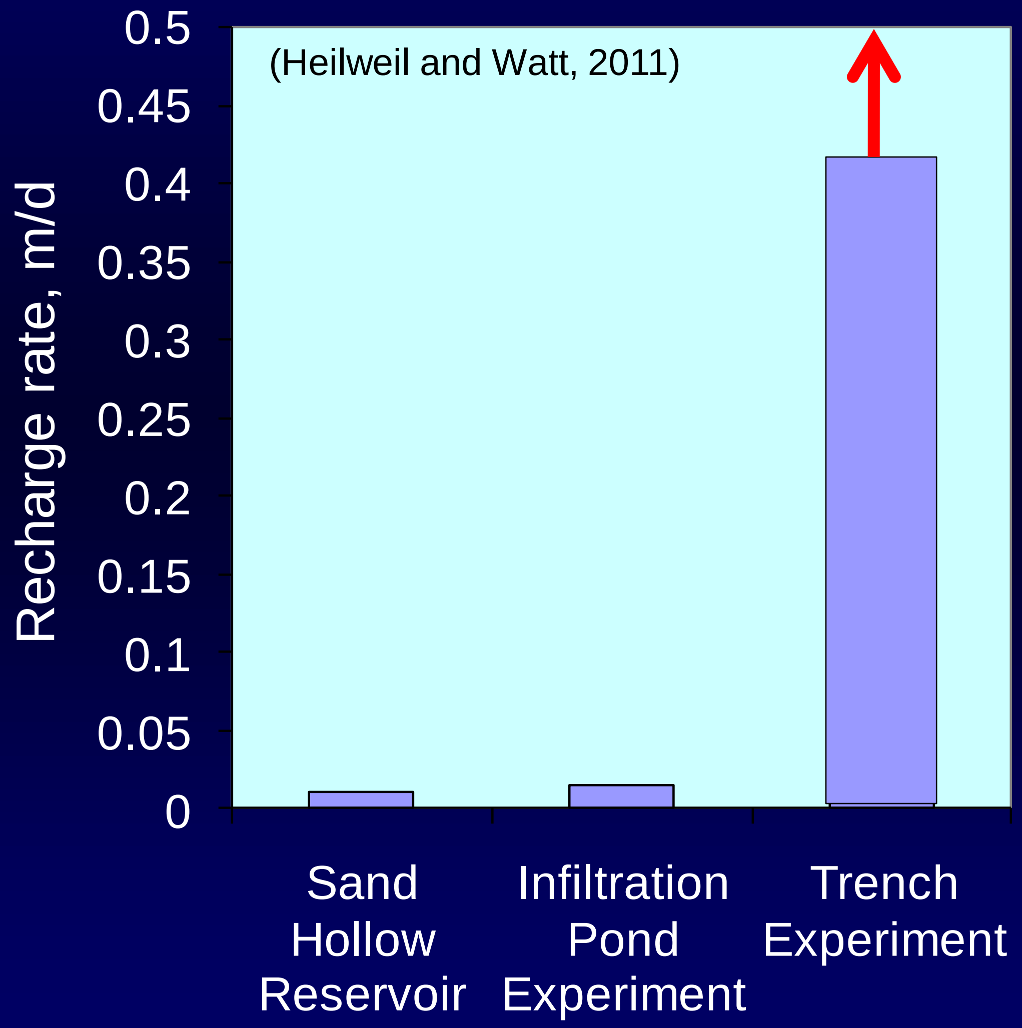



- Doubling of viscosity from summer to winter reduces hydraulic conductivity by 50 %
- Trench infiltration minimizes temperature variation

# Infiltration rates during Phase 3 are after connection with water table



# Comparison of Recharge Rates



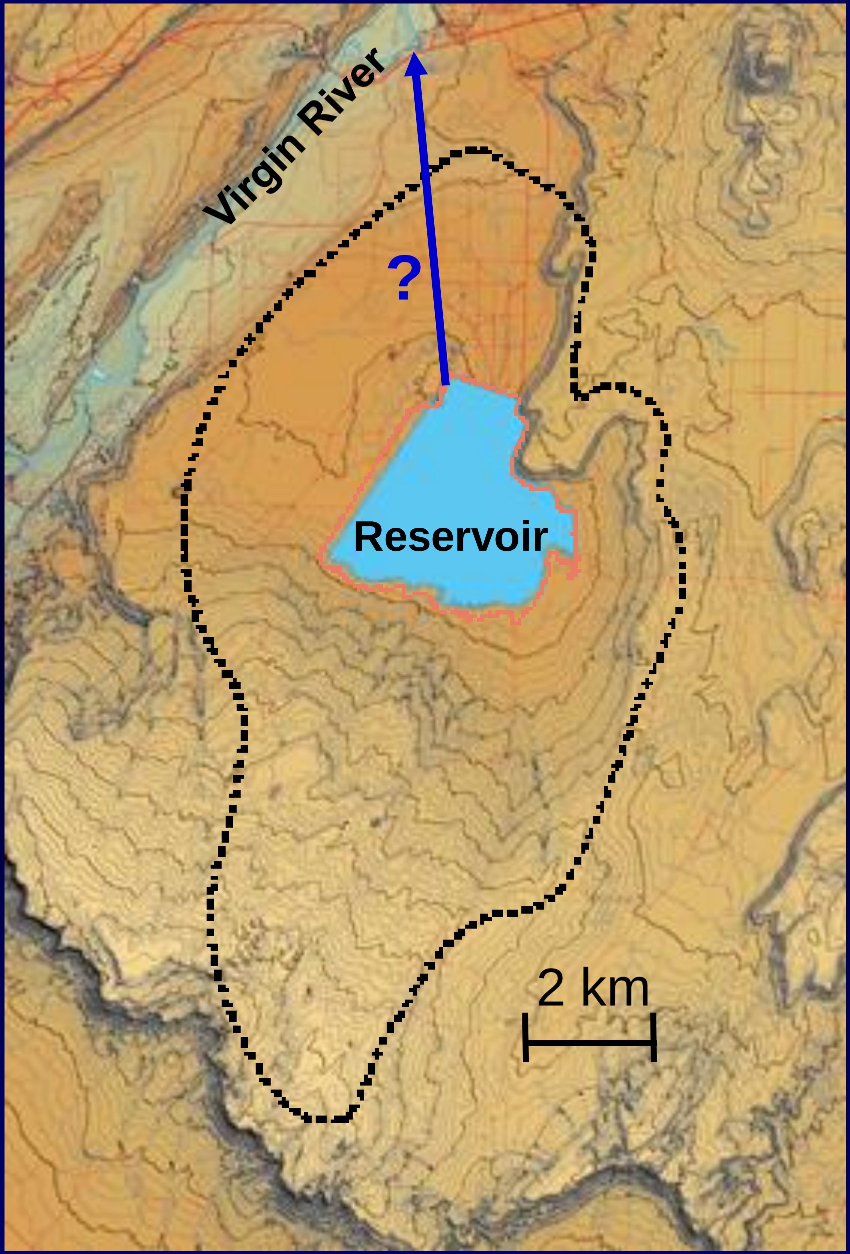

**Trench rates >> pond and reservoir rates**

- Access to open fractures
- Minimal physical clogging from biofilms or silt
- Minimal trapped air clogging due to lateral dissipation of trapped air
- Minimal biogenic gas production

# Trench infiltration could be used to enhance MAR at Sand Hollow and elsewhere in Colorado Plateau

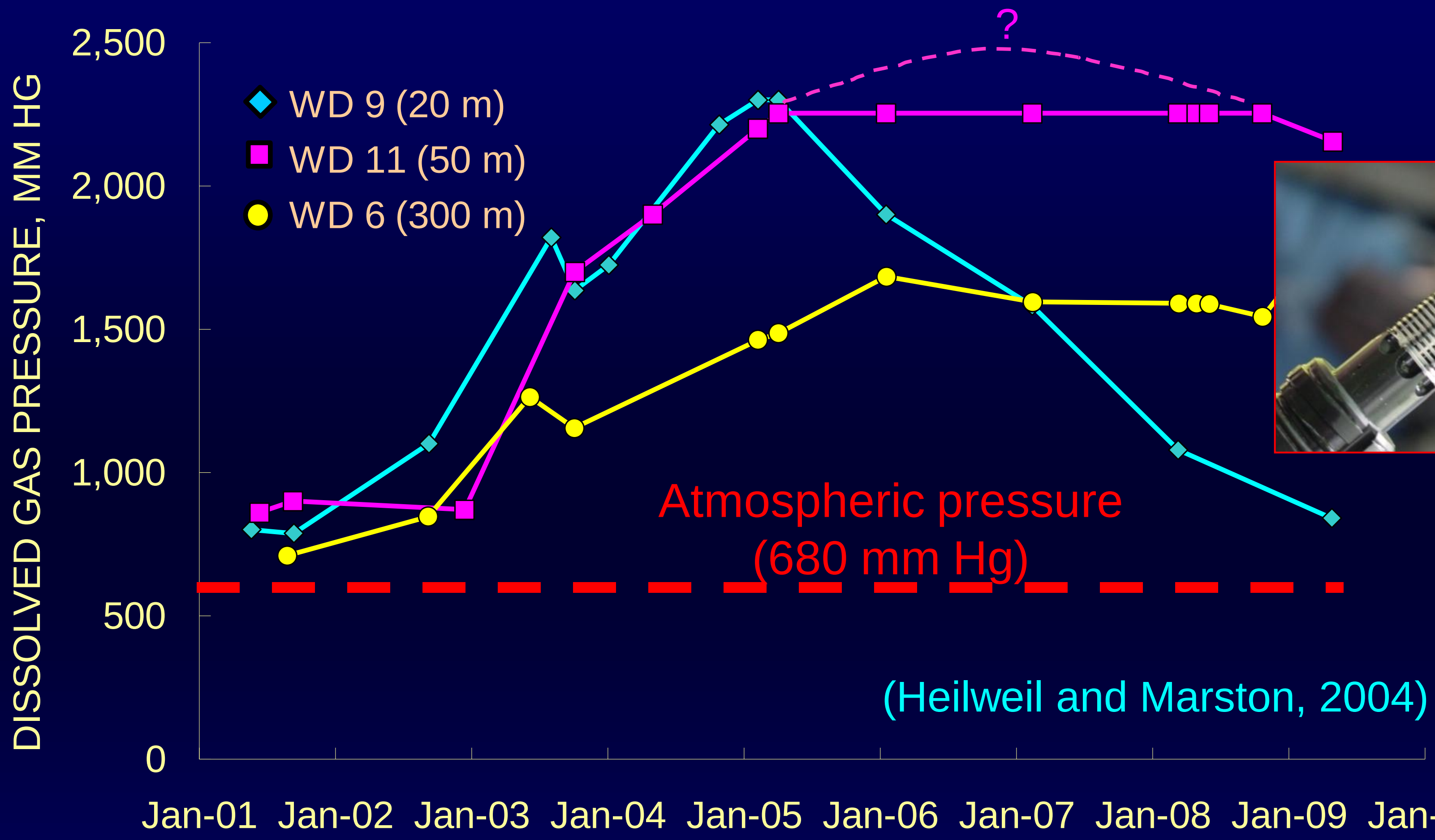
- Trenches could be located in upper part of Sand Hollow basin where deeper water table would maintain a vadose zone (unit hydraulic gradient)
- Trenches improve the feasibility of MAR in other sandstone outcrop locations where surface reservoirs cannot be constructed

# (C) Evaluation of Groundwater Residence Times




- Water managers need to know recovery timeline (e.g. travel time to Virgin River) and if MAR be relied upon through a 20-year "Megadrought"
- Tracers to evaluate travel times:
  - TDGP, Dissolved Oxygen, Ne Excess
  - Chloride/Bromide
  - Tritium, CFCs

# Total Dissolved-Gas Pressure (TDGP)

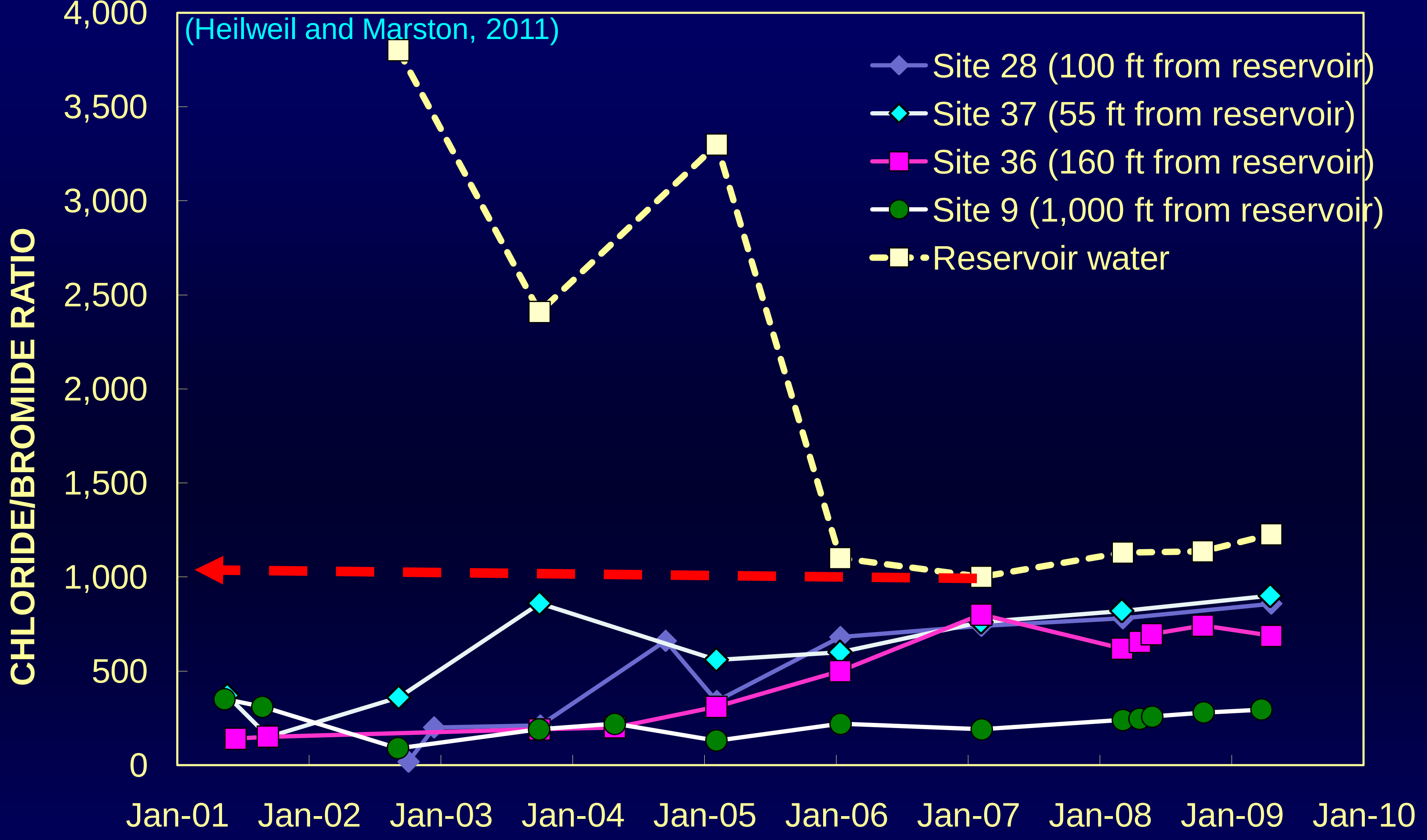



- Conservative tracer
- Measured with TDGP probe or Diffusion Sampler
- High pressures (> 3 atmospheres) = large amount of trapped gas

# Dissolved Gas Tracer Peaks

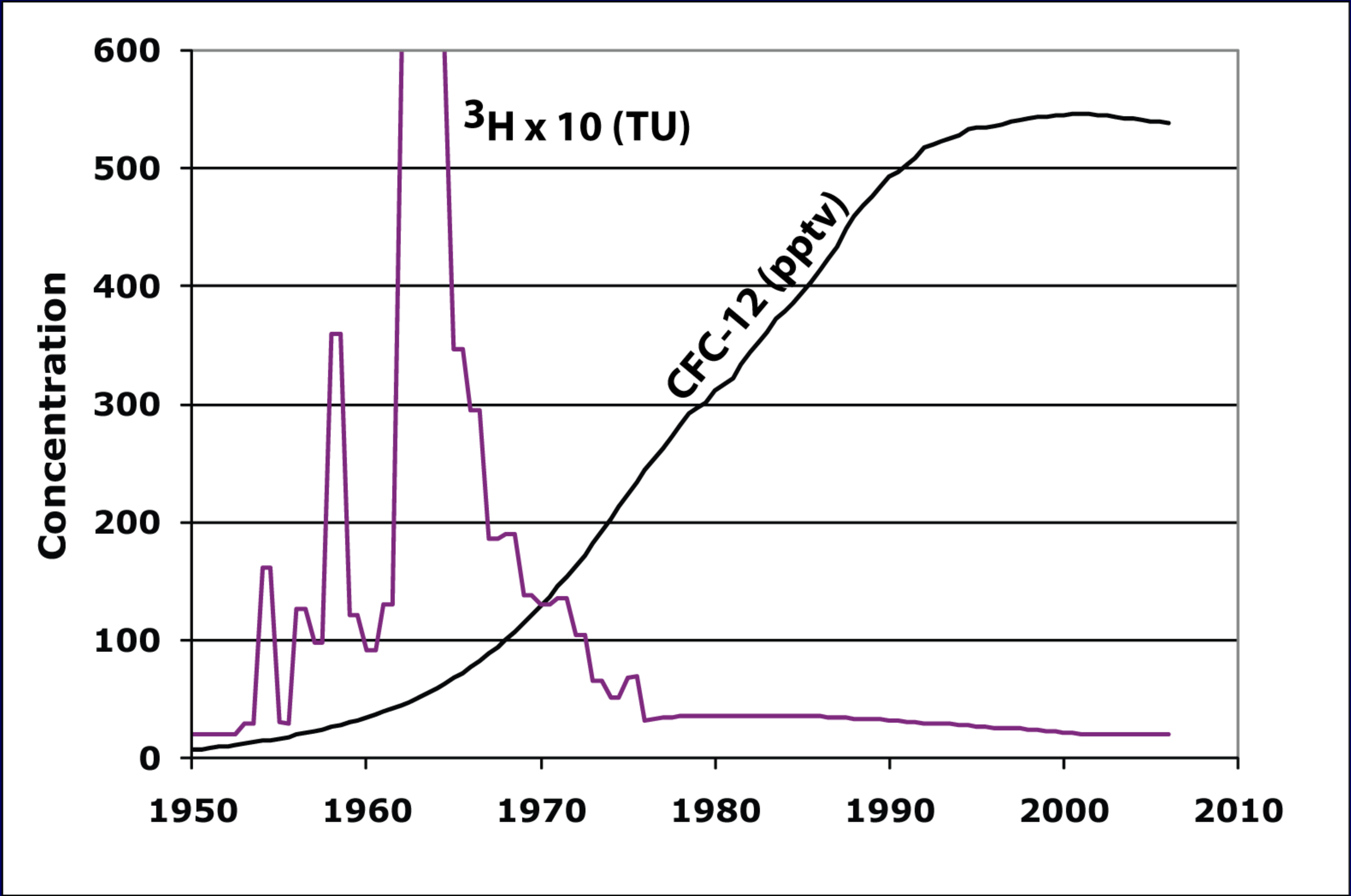
| Site | Distance from Reservoir (m) | Peak TDGP (mm Hg) | Peak DO (mg/L) | Peak Neon Excess |
|---|---|---|---|---|
| WD 9 | 20 | >2250 | 26 | 250% |
| WD 11 | 50 | >2250 | 25 | 320% |
| WD 6 | 300 | 1700 | 22 | 160% |

# Cl/Br Ratios




- Potential tracer of artificial recharge, but chloride/bromide of reservoir water has not been constant

# Tritium and CFC Atmospheric Input Functions




# Tritium ($^3H$)

- Conservative tracer of artificial recharge
- Background groundwater concentration < 0.1 TU
- "Modern" reservoir concentrations of about 4 TU
- Indicates that artificial recharge has migrated less than 1 km in 8 years

(Heilweil and Marston, 2011)


# CFC-12

- Background groundwater concentration < 10 pg/kg
- “Modern” reservoir concentrations of about 400 pg/kg
- Also indicates MAR has migrated less than 1 km in 8 years
- MODFLOW model calibrated to tracers indicate groundwater residence times of many decades

(Heilweil and Marston, 2011)

# Summary

- Bedrock MAR increasingly utilized to augment other water resources
- Vast storage potential of the Navajo Sandstone
- While declining recharge is typically attributed to siltation, other potential causes are hydraulic gradients, viscosity changes, biofilms, trapped gases
- Suite of environmental and geochemical tracers helpful for tracking movement of MAR through aquifer and indicates residence times of many decades
- Trench infiltration is a feasible future alternative for enhancing infiltration and targeting other sandstone outcrop areas

# References

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# Acknowledgements

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