Security of Stored Water
Water, Hydraulic Head, and Water Quality

Tom Sale
Emeritus Faculty
Colorado State University

2024 Subsurface Water Storage Symposium
CSU Spur Campus, Denver Colorado
February 22nd, 2024
SSWS Lots of “Ways” – Security depends on ...

Volume\textsubscript{in} v. Volume\textsubscript{out}  
Timing

Head\textsubscript{in} v. Head\textsubscript{out}  
Leakance

Consumptive Use  
Hydrogeology

ASR

Isolated Alluvial Storage

Return Flows
Where did it go - ASR

(Aquifer Storage and Recovery)
Particle Tracking
Think trampoline

Analytical Modeling of Particle Tracking for Dynamic Pumping Conditions
Yuan Cao¹ and Thomas Sala²

¹ Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL 32816, USA
² Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80523, USA. Thales.cao@ucf.edu
* Correspondence: yuan.ca@ucf.edu; Tel.: +1-407-823-7724


Dynamic gradient in the x and y directions from superposition of the Theis Solution in time

\[ h(x, y, t)_i = A_i x + B_i y + C - \sum_{j=1}^{m} \sum_{i=1}^{n} s(x, y, t)_{ij} \]

\[ \Delta x_i = \frac{-T}{b p} A_i \Delta t_i, \text{ and } \Delta y_i = \frac{-T}{b p} B_i \Delta t_i \]
130 Days
6000 Days (16 years)

“...result show that even under continuous pumping and injection, groundwater will not flow far from the well”
If OUT >> than IN...Like working at the bottom of a pit

- Drawdown from decades of pumping
- Mounding from recent recharge
~6 miles by 6 miles
Head

- Stored Water
- Energy
- Operational Issues
  - Sustaining flows
  - Protecting well screens (openings)
Herein, the analytical model of Lewis et al. (2016) was applied to three vertically stacked ASR wellfields using 15 years of pumping/recharge data from 40 wells. During the study period, 45 million m$^3$ of groundwater is produced and 11 million m$^3$ is recharged, leading to a net withdrawal of 34 million m$^3$ of groundwater.
Stored Water

Results indicate that during recovery and no-flow periods, recharge has increased water levels at wells up to 60 m compared to the no-recharge scenario. On average, the recharge increased water levels during the study period by 3, 4, and 11 m for wells in the Denver, Arapahoe, and Laramie Fox-Hills Aquifers, respectively.

Denver Basin Aquifers, recharge also enables groundwater extraction in excess of allowable annual allocations during periods of high demand including drought.
Head and Energy

Colorado Water

Evaluating the Energy Cost of Groundwater Production in the Denver Basin Aquifers

Figure 2. Example data for a municipal well in the Denver Basin. The wellhead elevation is 1,560 meters above mean sea level (in srms), indicating water depths ranging from 230 to 420 m below ground surface. Measured water levels are shown as open circles; pumping rates are shown as grey bars.
...the energy cost associated with lifting water is 5.4 kWh day$^{-1}$ per household, approximately 25% of the average electricity consumption for household end uses.
Operational Issues

Aquifers work better when they are full

• Sustaining flows

• Protecting well screens (openings)
Water Quality

• It all depends...

• Lots of operational solutions
Summary - Security of Stored Water

- ASR
  - Easy to hard
  - Operational Solution for ...

- Isolated Alluvial
  - Mostly easy
  - Needs to be demonstrated

- Return Flows
  - Complicated
  - Defined Process
  - WORKS
In all fairness... Security of Subsurface v. Surface Water

Losses (acre-ft/year)

| 1,000,000 | ~$50,000 /acre foot | $50,000,000,000 |
| 700,000   |                   | $35,000,000,000 |

Value of Water Rights

Not to mention water quality ... Evapo-Concentration of salts

https://www.nps.gov/glca/index.htm
Closing and Comments

“A synergistic complement

“The redemption of the Arid Region involves engineering problems requiring for their solution the greatest skill.”

Powell’s Retirement

Image: Torpy - CC BY-SA 4.0, via Wikimedia Commons