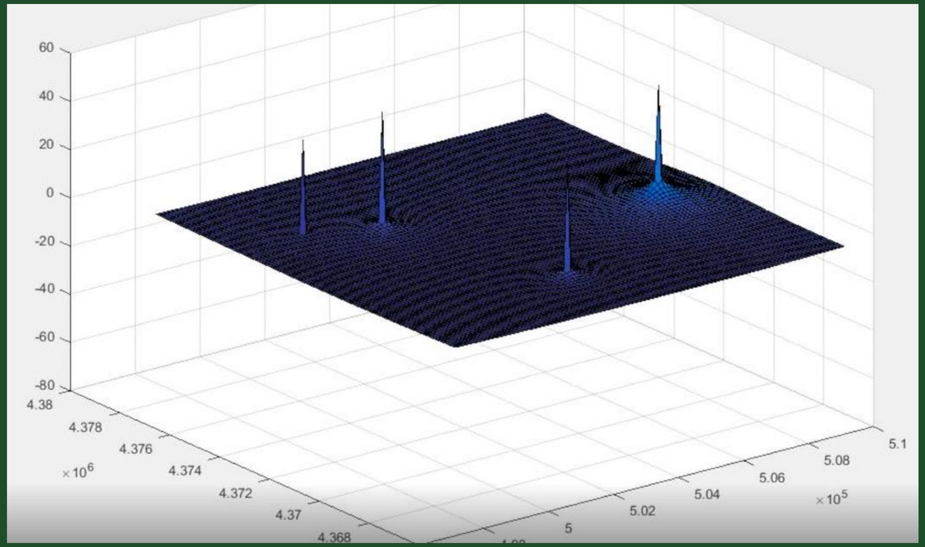
Security of Stored Water

Water, Hydraulic Head, and Water Quality

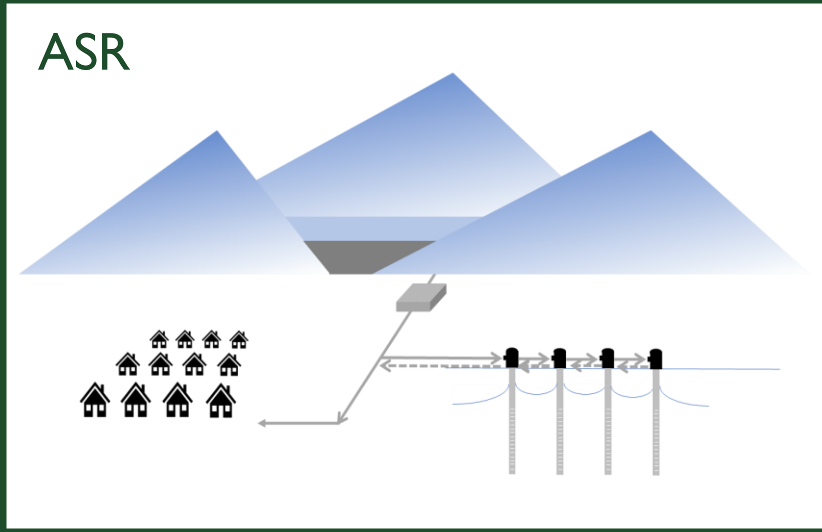


Tom Sale

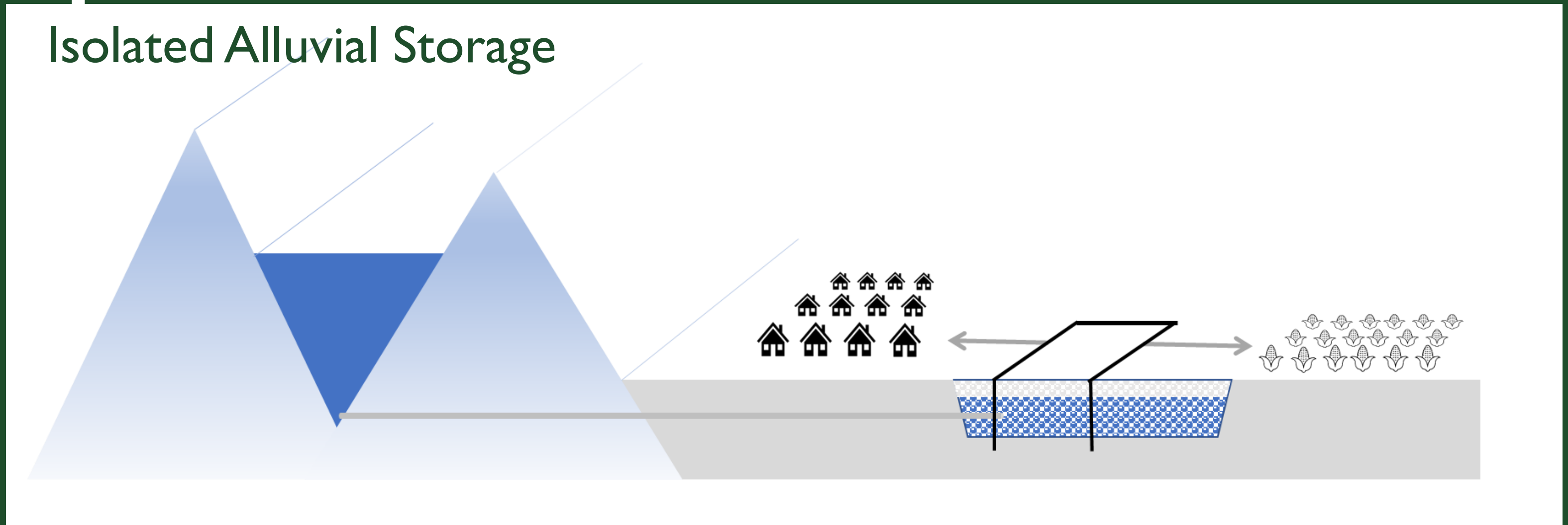
Emeritus Faculty
Colorado State University

2024 Subsurface Water Storage Symposium
CSU Spur Campus, Denver Colorado
February 22nd, 2024

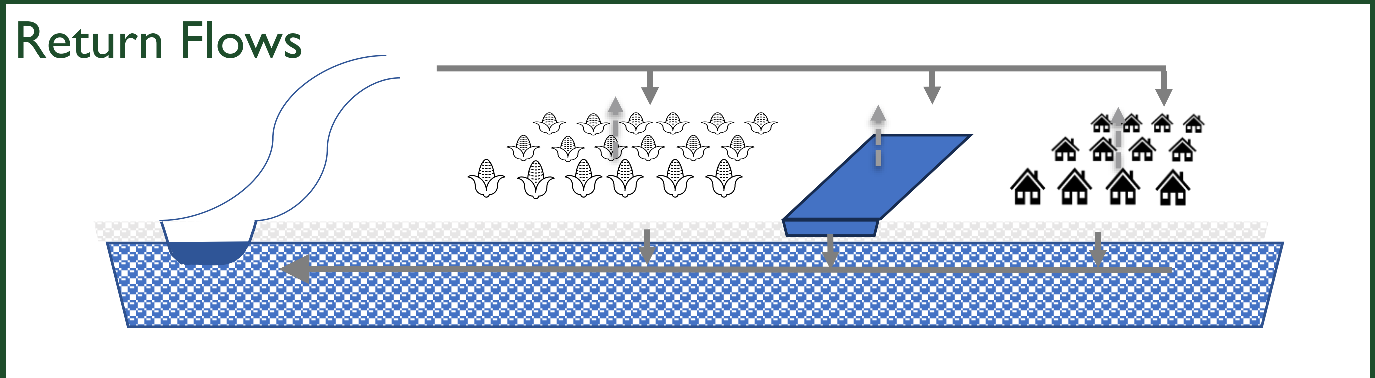
SSWS Lots of “Ways” – Security depends on …



$$Volume_{in}\ v.\ Volume_{out}$$
Timing



$$Head_{in}\ v.\ Head_{out}$$
Leakance

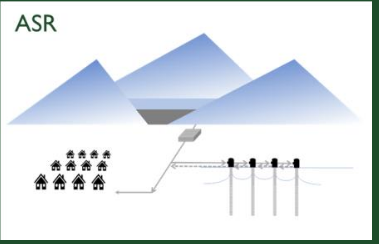


Consumptive Use
Hydrogeology

What is Glover solution?

The Glover-Balmer Solution was developed in 1954 by Robert Ellsworth Glover and Glenn G. Balmer. This analytical solution for estimating impacts to streamflow from the pumping or recharge of alluvial aquifer systems is often simply referred to as the Glover Equation.

Nov 3, 2020



Where did it go - ASR

(Aquifer Storage and Recovery)

Particle Tracking

Think trampoline

water MDPI

Article

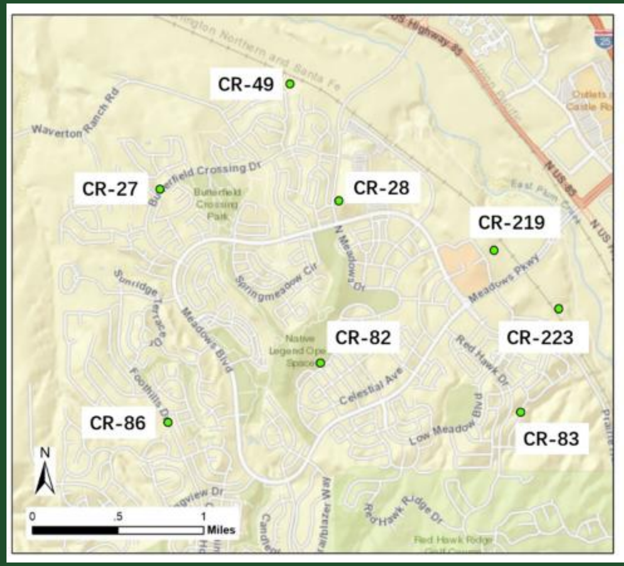
Analytical Modeling of Particle Tracking for Dynamic Pumping Conditions

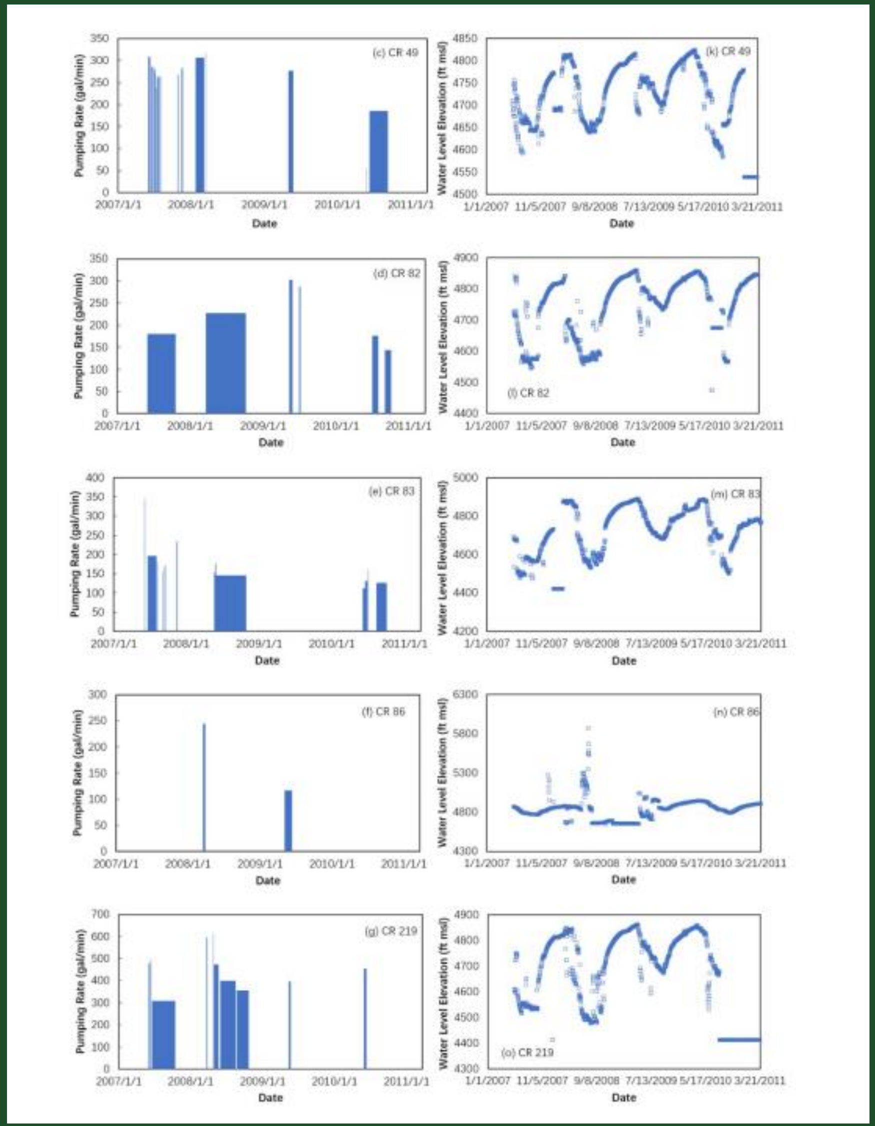
Yuan Gao [1,*] and Thomas Sale [2]

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; TSale@engr.colostate.edu
* Correspondence: yuan.gao@Knights.ucf.edu; Tel.: +1-970-581-7124

27. Lewis, R.A.; Ronayne, M.J.; Sale, T.C. Estimating aquifer properties using derivative analysis of water level time series from active well fields. *Groundwater* **2015**, *54*, 414–424. [CrossRef] [PubMed]

24. Davis, J.A. Coupled Analytical Modeling of Water Level Dynamics and Energy Use for Operational Well Fields in the Denver Basin Aquifers. Master's Thesis, Colorado State University, Fort Collins, CO, USA, 2013.



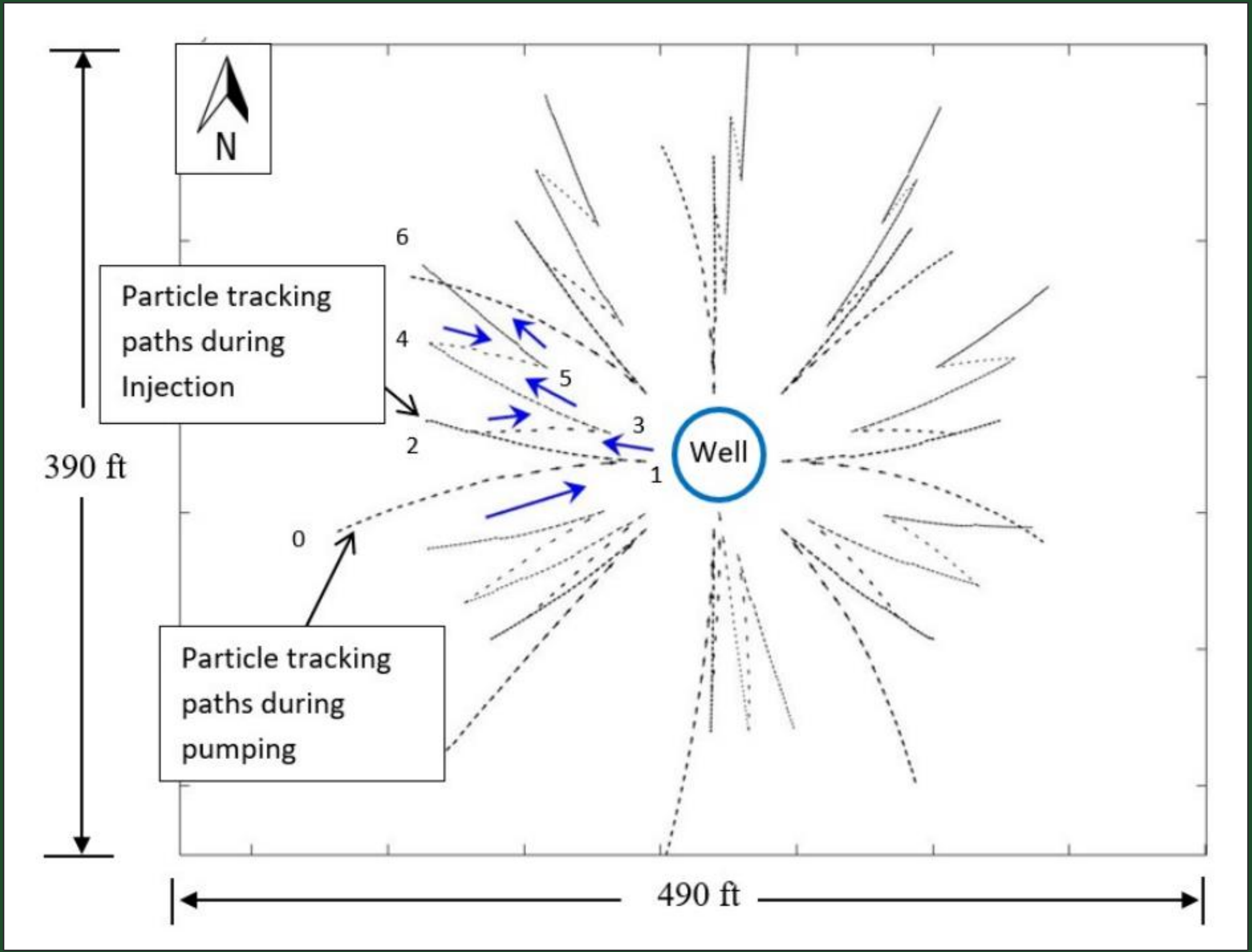


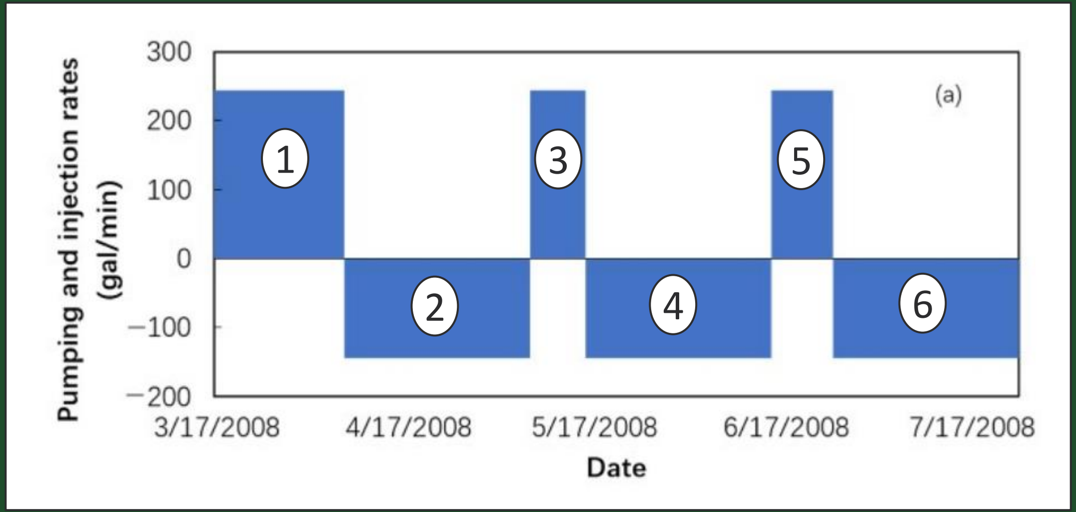
Dynamic gradient in the x and y directions from superposition of the Theis Solution in time

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

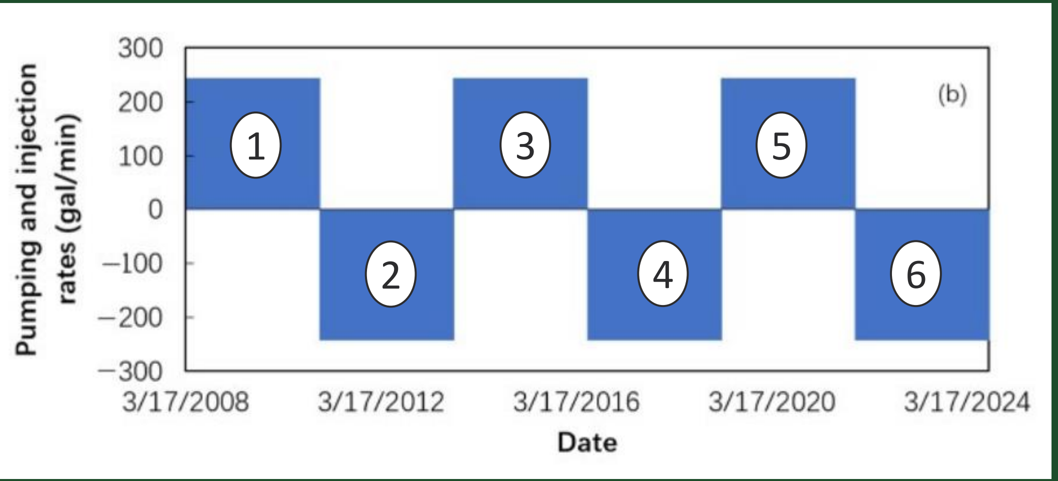
$$\Delta x_i = \frac{-T}{b\varphi} A_i \Delta t_i, \text{ and } \Delta y_i = \frac{-T}{b\varphi} B_i \Delta t_i$$

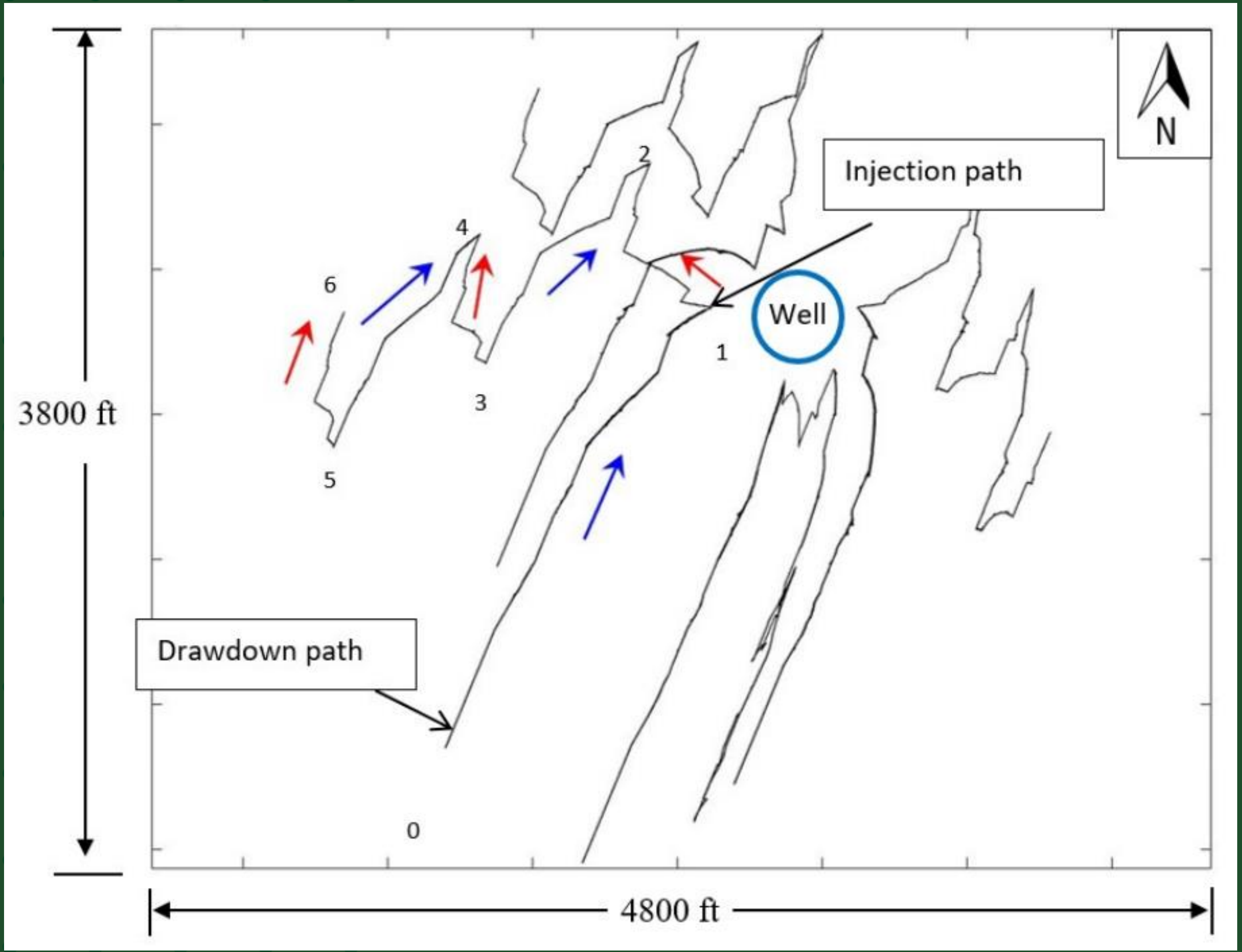
130 Days


N
Particle tracking paths during Injection
Particle tracking paths during pumping
Well
0
1
2
3
4
5
6
390 ft
490 ft


Pumping and injection rates (gal/min)
300
200
100
0
−100
−200
3/17/2008
4/17/2008
5/17/2008
6/17/2008
7/17/2008
Date
(a)
1
2
3
4
5
6

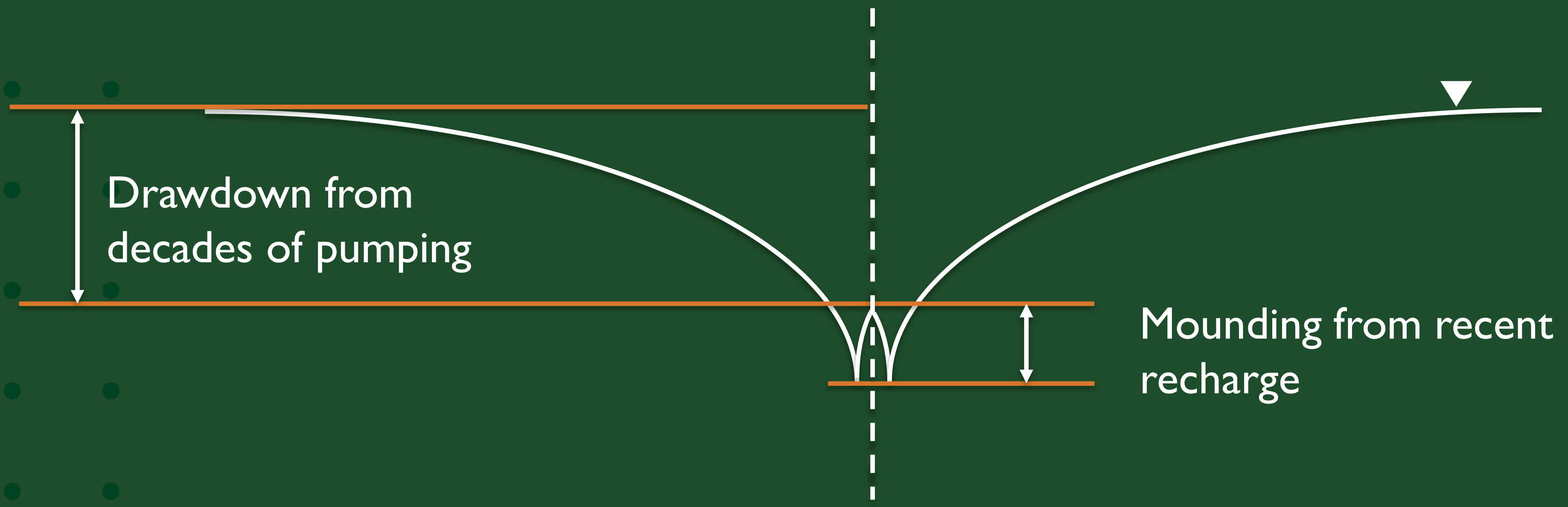
6000 Days (16 years)





"… 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



~6 miles by 6 miles

Center for
Contaminant Hydrology

ASR Wellfield Water Levels

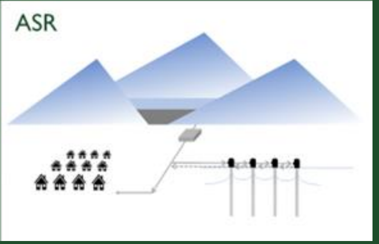
Original work: 2018

Credits:

Dr. Mike Ronayne and Dr. Ali Abdulaziz
Tom Sale, Prof., Colorado State University

Produced by:

Emma Schmit
2022



Head

- Stored Water
- Energy
- Operational Issues
  - Sustaining flows
  - Protecting well screens (openings)

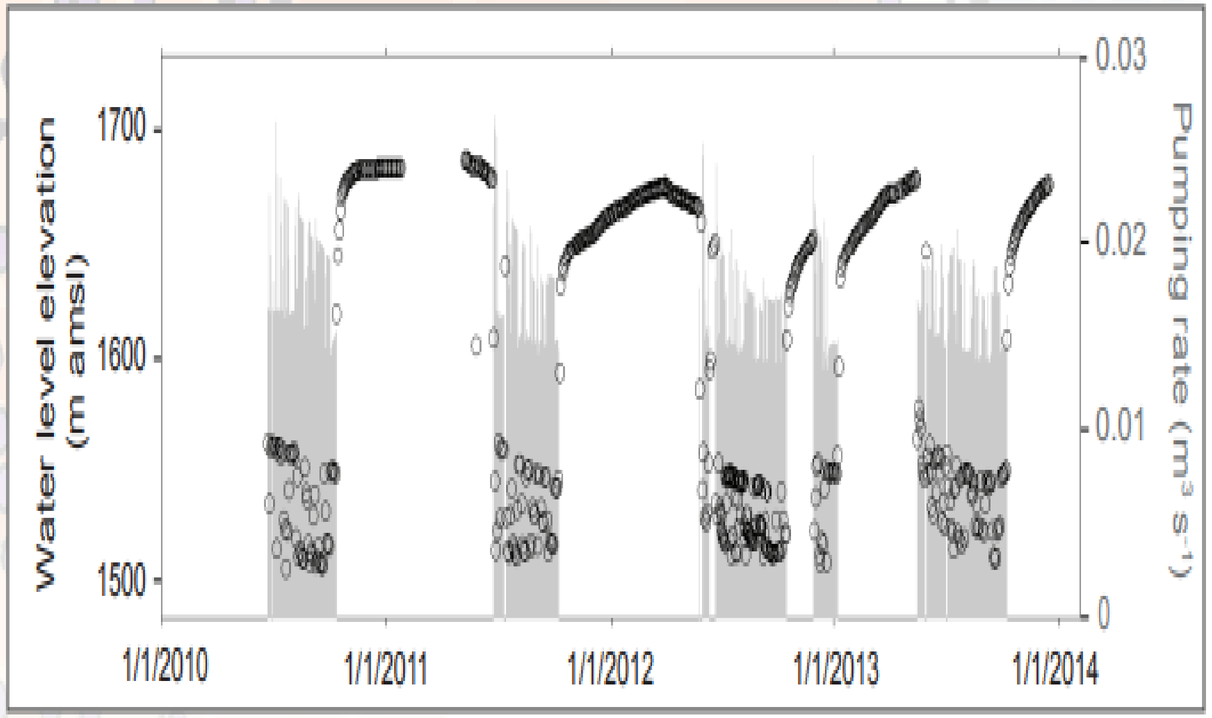
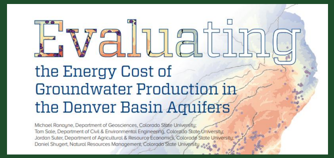
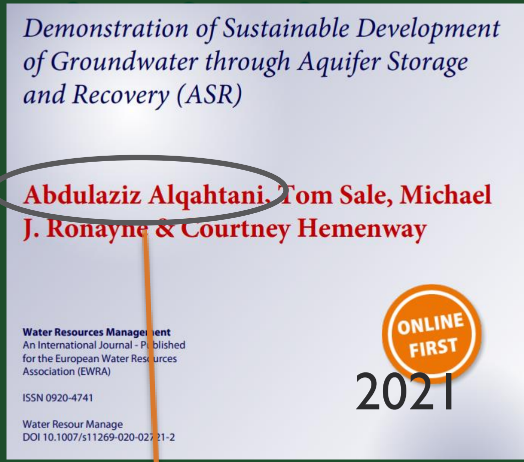


Figure 2. Example data for a municipal well in the Denver Basin. The wellhead elevation is 1,920 meters above mean sea level (m amsl), indicating water depths ranging from 230 to 420 m below ground surface. Measured water levels are shown as open circles; pumping rates are shown as grey bars.



Stored Water

Herein, the analytical model of Lewis et al. (2016) was applied to <u>three vertically stacked ASR wellfields using 15 years of pumping/recharge data from 40 wells</u>. During the study period, <u>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</u>


Demonstration of Sustainable Development of Groundwater through Aquifer Storage and Recovery (ASR)

Abdulaziz Alqahtani, Tom Sale, Michael J. Ronayne & Courtney Hemenway

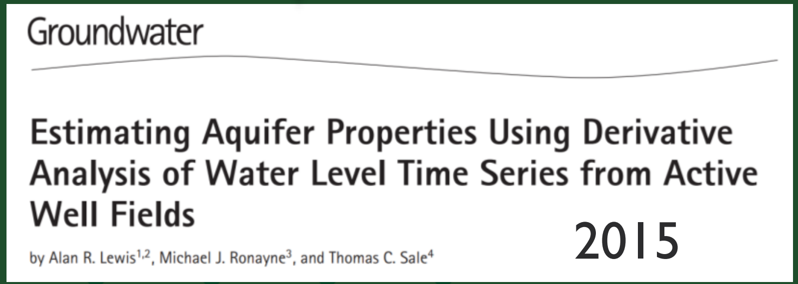
Water Resources Management
An International Journal - Published for the European Water Resources Association (EWRA)

ISSN 0920-4741

Water Resour Manage
DOI 10.1007/s11269-020-027?1-2

ONLINE FIRST

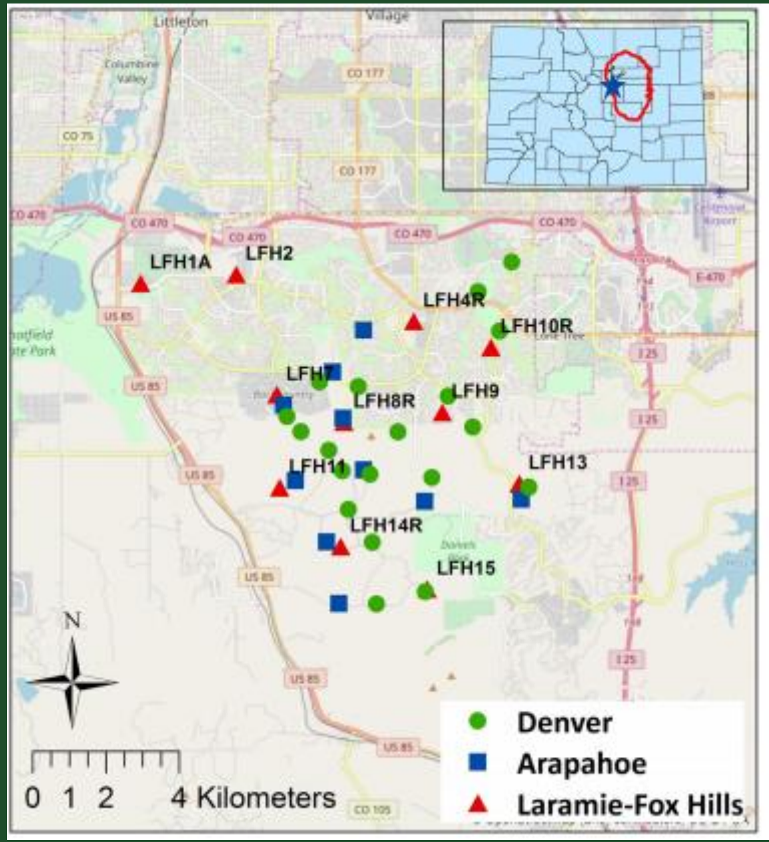
2021

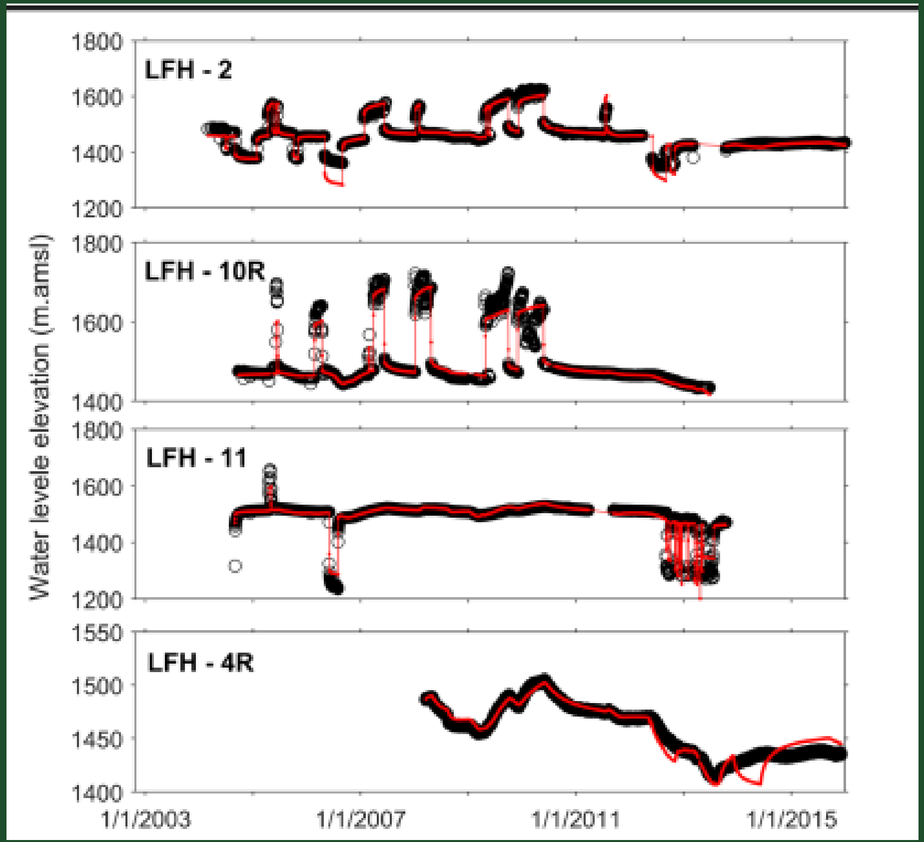

Groundwater

Estimating Aquifer Properties Using Derivative Analysis of Water Level Time Series from Active Well Fields

by Alan R. Lewis[1,2], Michael J. Ronayne[3], and Thomas C. Sale[4]

2015





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

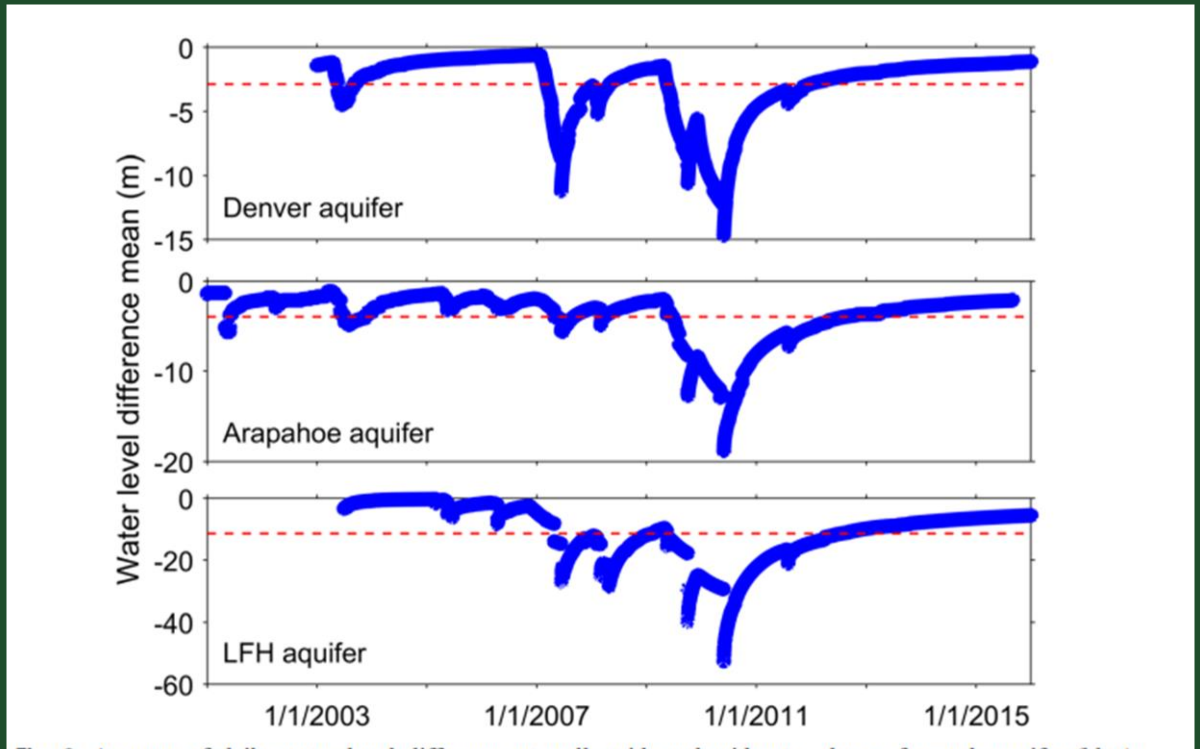
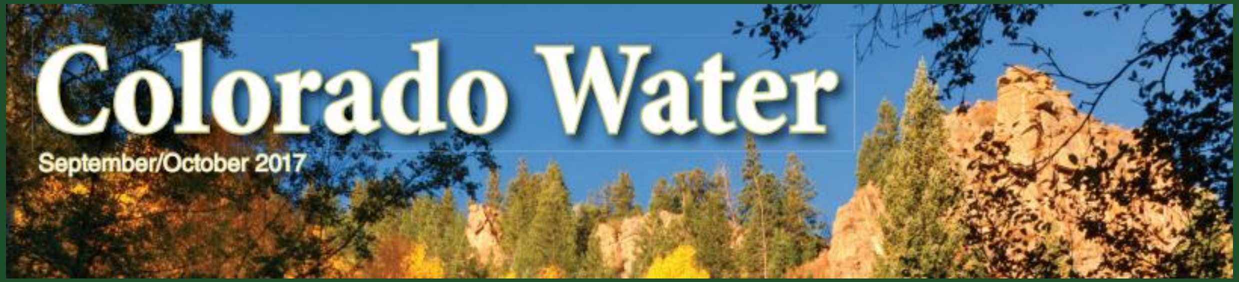
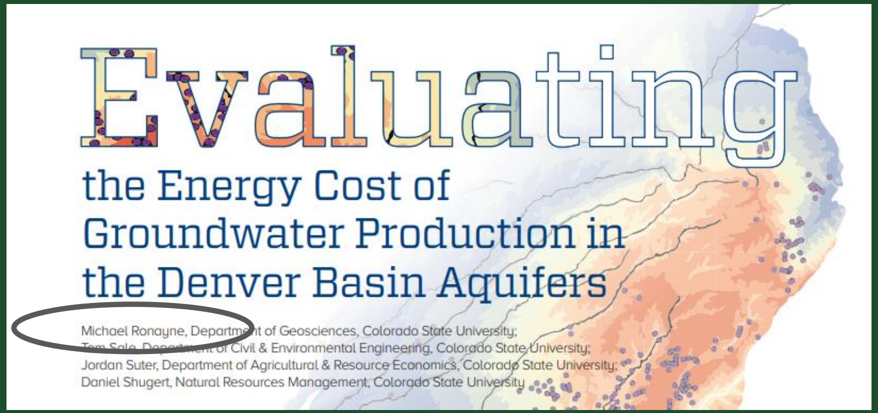


Fig. 8 Average of daily water level difference at wells with and without recharge for each aquifer (blue); historical average (all times) of water level difference at wells with and without recharge for each aquifer (red)

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

Head and Energy





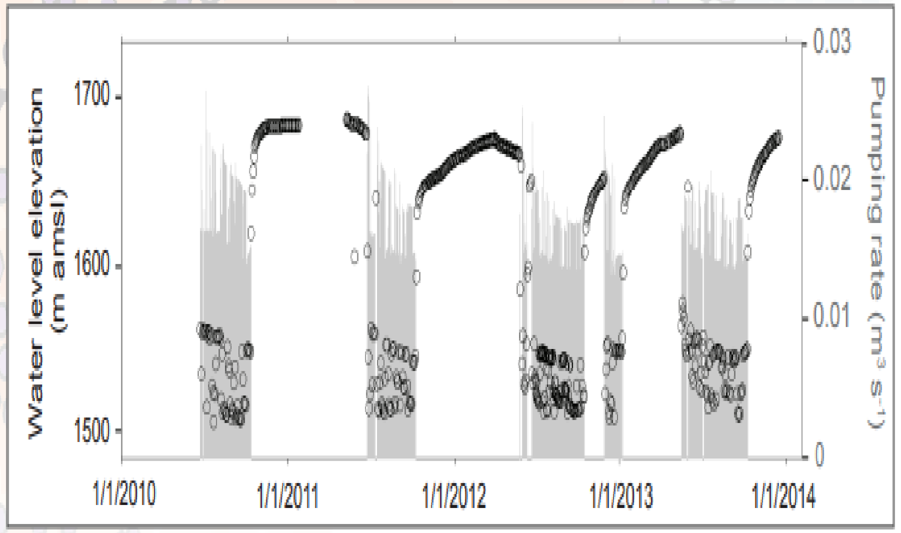


Figure 2. Example data for a municipal well in the Denver Basin. The wellhead elevation is 1,920 meters above mean sea level (m amsl), indicating water depths ranging from 230 to 420 m below ground surface. Measured water levels are shown as open circles; pumping rates are shown as grey bars.

ASR

Energy Intensity

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

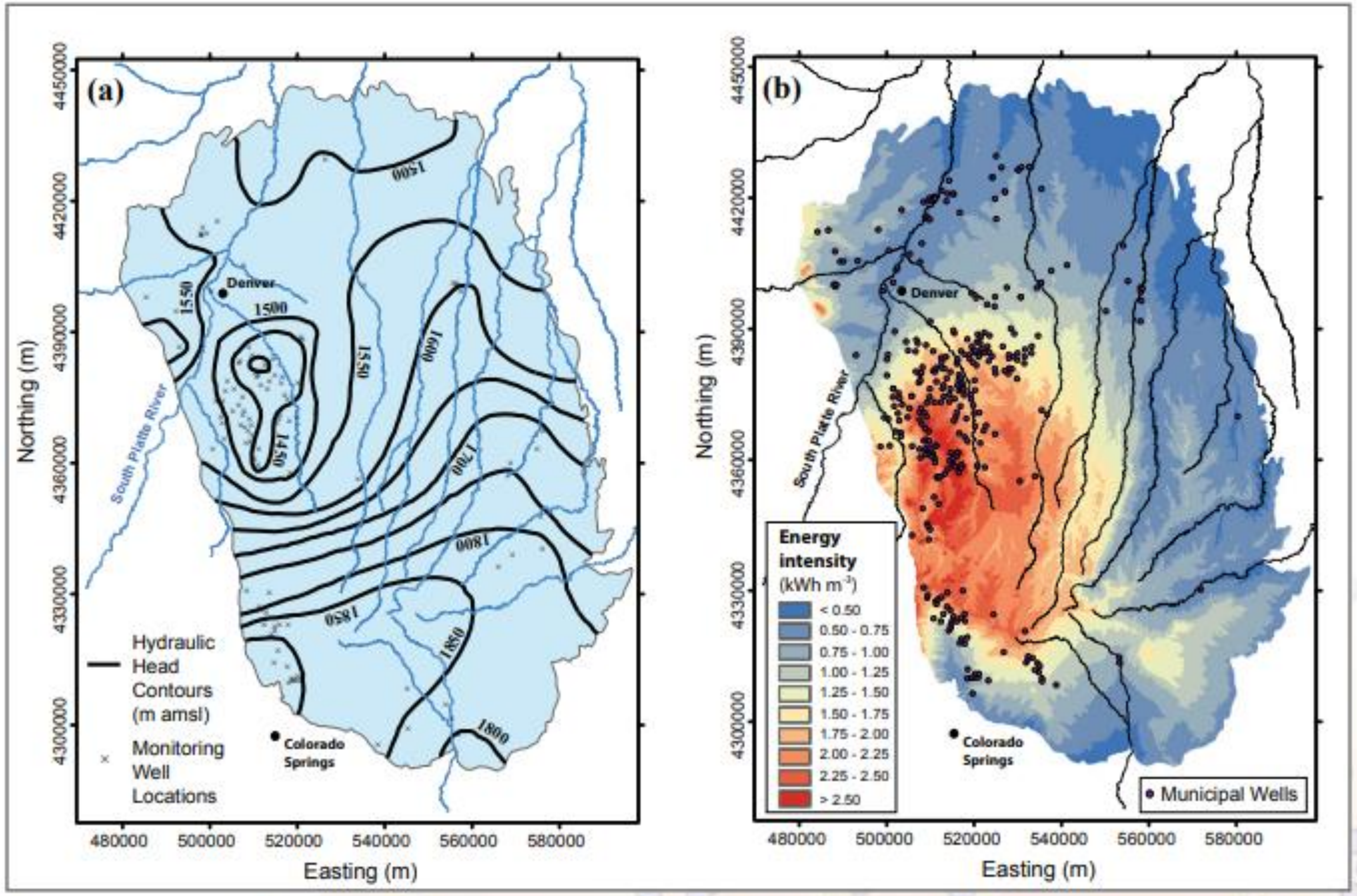


Figure 3. (a) Arapahoe Aquifer potentiometric surface map and (b) estimated energy intensity for groundwater pumping in the Arapahoe Aquifer. Circles represent active municipal wells.

…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

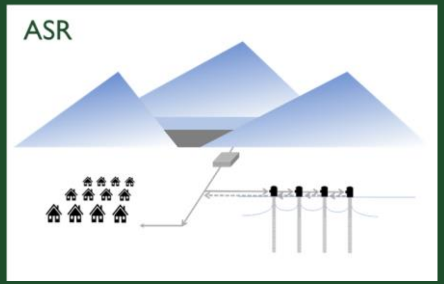
Aquifers work better when they are full

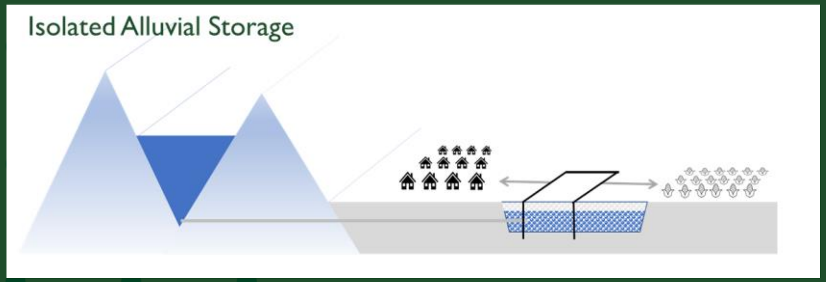
- Sustaining flows
- Protecting well screens (openings)

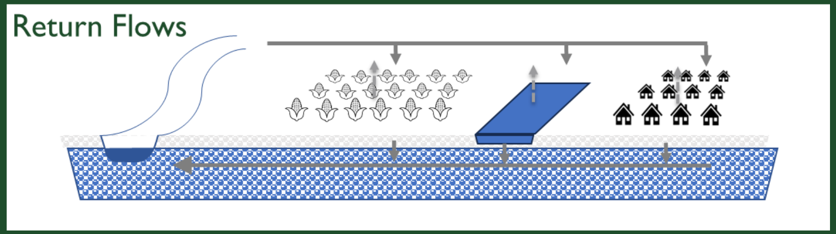
Water Quality

- 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

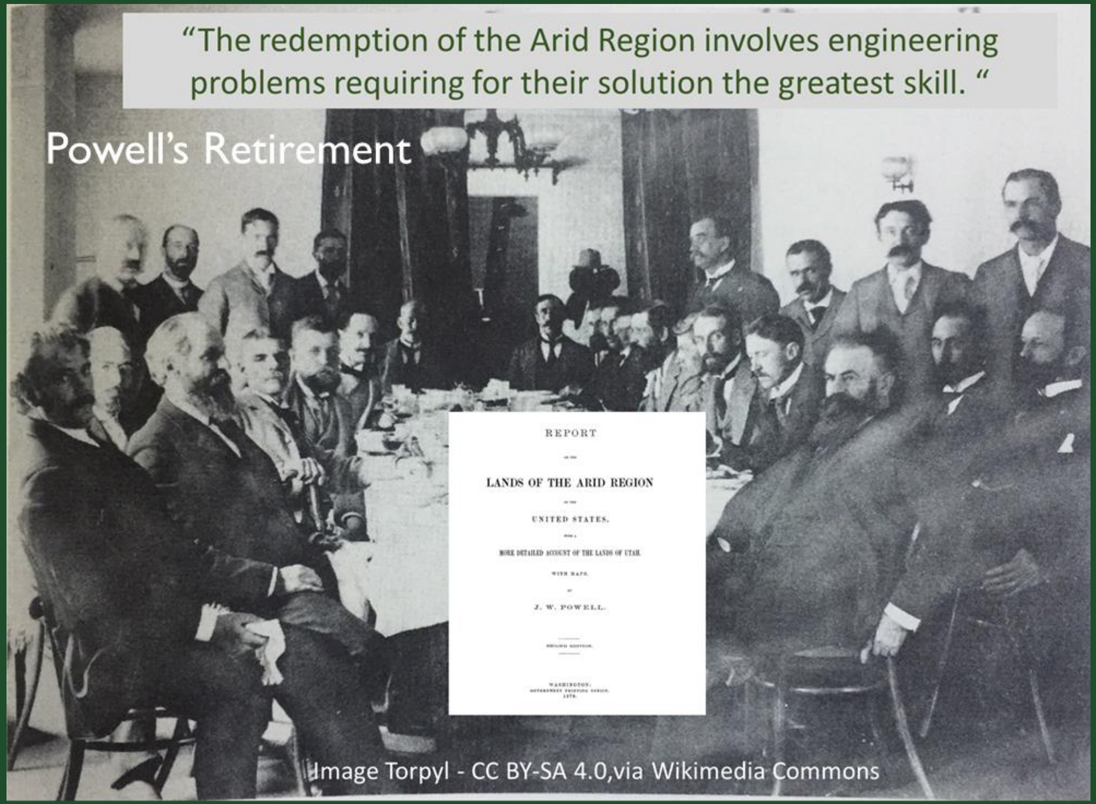
In all fairness... Security of Subsurface v. Surface Water

Losses (acre-ft/year)		Value of Water Rights		
1,000,000	→	~$50,000 /acre foot	→	$50,000,000,000
700,000				$35,000,000,000

B

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

Closing and Comments



A synergistic complement