September 26, 2023

Presenter/ Comment by	Type	Title	Approximate time
	NDWR Welcome		1:00 PM - 1:10 PM
Collins, Ryan	Presentation	SLO - Conservation though better management of the Humboldt Decree	1:10 PM - 1:35 PM
Gallegos, Erica	Presentation	NGM - Future water management in the Humboldt River region	1:35 PM - 2:00 PM
Smith, Dwight and Dixon, Jay	Presentation	Dixon et al. - Groundwater pumping from distant locations for flow augmentation the Humboldt River	2:00 PM - 2:25 PM
Skulan, Caitlin	Presentation	SLO - Funding sources for Water Master, river management, and gaging	2:25 PM - 2:50 PM
Skulan, Caitlin	Comment	SLO - Updated conjunctive management "white paper" submission	2:50 PM - 3:00 PM
	Break		3:00 PM - 3:15 PM
Scott, Bruce	Comment	RCI - Water flow probabilities by river segment	3:15 PM - 3:25 PM
Taylor, Michael	Presentation	UNR - Humboldt River water valuation and transaction strategies	3:25 PM - 3:50 PM
Barrie, Maddie	Presentation	TNC - Nature-based solutions on the Humboldt River	3:50 PM - 4:15 PM
Smith, Dwight	Presentation	SLO - Modeling tool updates and uses related to allocations of costs for management of the river	4:15 PM - 4:40 PM
General Comment and Discussion session			4:40 PM - 4:55 PM

Conservation of Water Through Better Management on the Humboldt River

Utilizing tighter deliveries on priority and hiring more personnel to administer water deliveries

Ryan Collins, Manager

Pershing County Water Conservation District

Lovelock, Nevada

pcwcd@irrigation.lovelock.nv.us

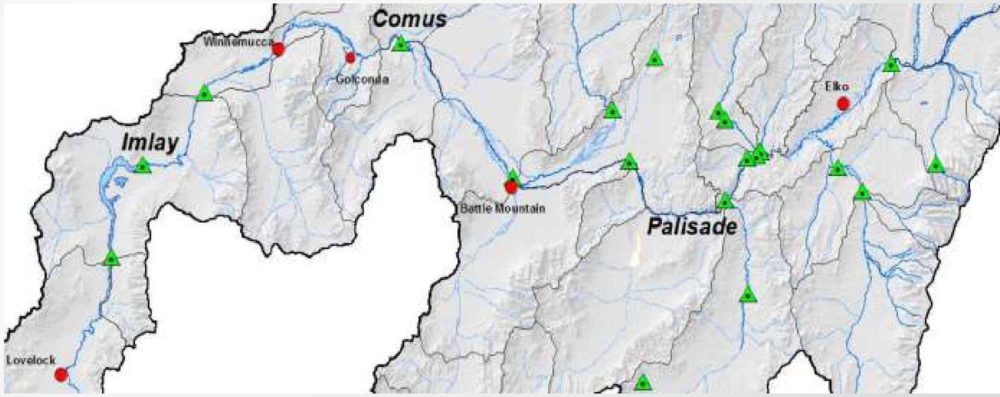
- Addressing both surface water and groundwater individually, as well as conjunctively, can help lead to a more sustainable and reliable water system.
- To help surface water shortages on the Humboldt River and its tributaries, tighter and better management of the system can be implemented.

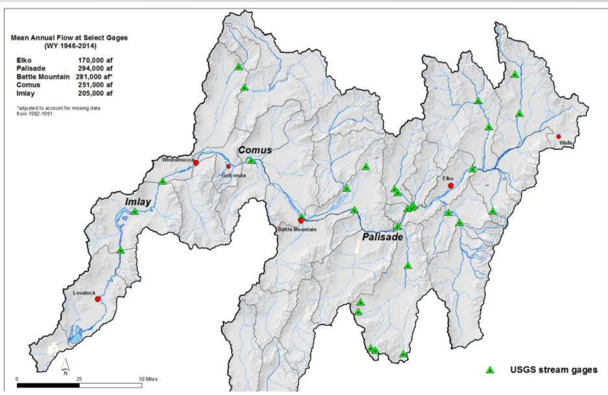
- Recommendations are based on years of observing the management on the Humboldt River
- Pershing County Water Conservation District has noticed several areas where the system can be better managed,

These include:

River Commissioners should serve the same priority below Palisade as above Palisade, as decreed.

- For example, on April 1, 2022:
- 109 CFS at Palisade, enough to serve an 1870 (91 CFS) to all the users below Palisade
- However, at Battle Mountain, flow was 69 CFS
- And, at Comus, flow was 65 CFS
- With 25% figured in for conveyance loss, there isn't enough water to serve 1870 priorities, at Battle Mountain or downstream





- River Commissioners should not raise or change priority of water service until all the current (senior) priority deliveries are actually served.

- River Commissioners would use latest Snotel and Streamflow forecast to help make these decisions.

The Decree does not stipulate that the priorities should be based on the flow at Palisade, but it does state that where the years are the same priorities are equal.

- Require all water deliveries be made by River Commissioners
- *Individual water users should not be allowed to operate their own delivery gates.*

- Providing transparency by creating a real-time database for all surface water delivery records on the Humboldt River and its tributaries available to the public.
- All water users should know what year of priority is being served over the entire system.

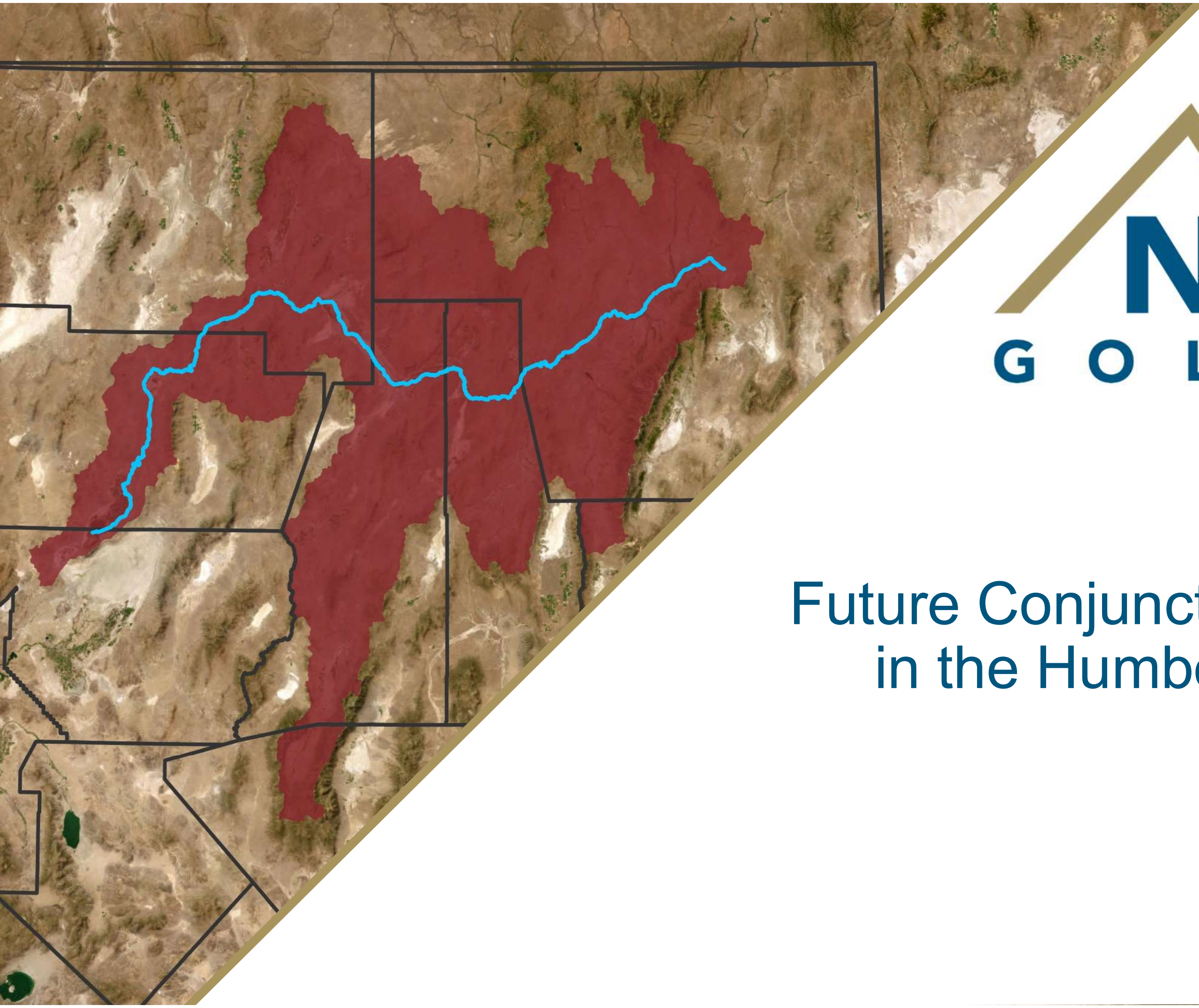
- Creating a real-time, publicly available database for all stream measurement stations for flow and elevation, and thereby limiting the “measurement & shift” issues that create issues for stream gauge.

- Re-installing a river gauge at Rose Creek in the Winnemucca area.
- There is a large loss of river water through the Winnemucca segment.
- A gauge at Rose Creek would assist in monitoring and tracking river loss between Comus and Winnemucca.

- Consider an increase in assessment:

  There is already an assessment on the water users, and if more funding is needed to properly administer the decree as it is written an increase in the assessment might be necessary.

Some of these concepts can be implemented immediately based on the decree.



NEVADA GOLDMINES

Future Conjunctive Management in the Humboldt River Region

September 26, 2023

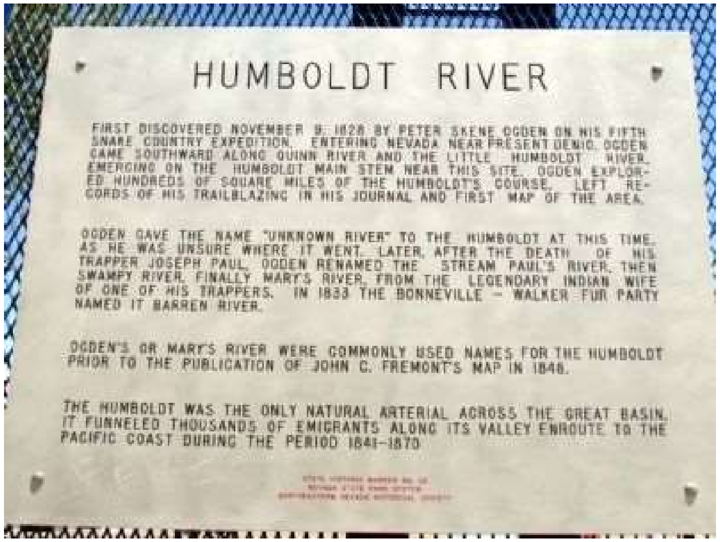
Erica Gallegos
NGM

From the Beginning…

Statutes relating to water law were enacted by the NV Legislature as early as 1866 and in 1913 water law was rewritten to fully recognize underground water

A new legislative chapter was established in 1939 which clearly defined the separation of the two sources under law and provided for the appropriation of percolating groundwater rights.

A legislative declaration was adopted in 2017 regarding conjunctive management – **a century of water law recognizing surface water and groundwater as distinct sources**

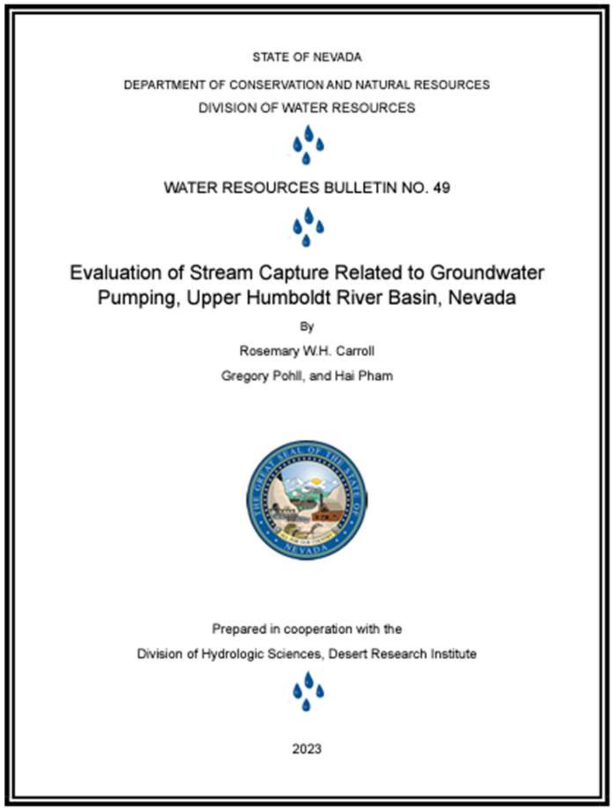


NRS 533.025: **"The waters of all sources of water supply within the boundaries of the State, whether above or beneath the surface of the ground, belong to the public."**

Conjunctive Management

"Conjunctive Water Management" is managing and using water resources that combines surface water and groundwater in a coordinated manner as a single source and recognizing the interaction between the two.

- Understanding the connectivity of systems is still uncertain in many areas of Nevada
  - According to the recently published Upper Humboldt River Model:
    - *"…this revised understanding combined with other model limitations effectively limits the ability of this model to estimate stream capture from pumping in the Upper Humboldt River Basin."*
      - Which begs the question on how this model will be utilized for modeling capture



STATE OF NEVADA

DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

DIVISION OF WATER RESOURCES

WATER RESOURCES BULLETIN NO. 49

Evaluation of Stream Capture Related to Groundwater Pumping, Upper Humboldt River Basin, Nevada

By

Rosemary W.H. Carroll

Gregory Pohll, and Hai Pham

Prepared in cooperation with the

Division of Hydrologic Sciences, Desert Research Institute

2023

Goals and Objectives

Conjunctive Management is Multidimensional

comprised of economic, social, and scientific goals and objectives

What are we trying to achieve, and can we measure that success?

- Economic benefit? Social benefit?
  - Who benefits and who suffers injury?
- Downstream users receiving full duty?
  - Is this physically possible?
- Is this an engineering problem or is this a management problem? Or both?
- How do we measure success?
- Stakeholders, together with the Nevada legislature need to define the goals and objectives

Implementation

It's important to understand the history and how to carefully put two concepts together physically, legally, socially, and economically that have been recognized as separate sources for 100 years.

Considerations:

- Thorough thought-out process to research and develop concepts, management, feasibility, effects, and legislative authority
  - The foundation of conjunctive management in Idaho was established in 1951 and decades later implementation occurred
- Clearly defined goals and objectives
- Zero-sum approach
  - Curtailment will have an economic impact – especially those that are junior and do not capture from the Humboldt River – not only to the water rights holders but, to the community as well
  - Just because the basins are over appropriated does not mean they are over pumped
- Public access to all the Humboldt River Models
  - Lack of certainty in published model
  - Exceeded scheduled deliverable deadlines; question feasibility of future updates
- Development of working groups involving various stakeholders to collaborate on conjunctive management working towards the defined goals and objectives

Other Tools and Considerations

- Water banking and storage
- Aquifer storage and recovery/recharge
- Flow augmentation
- Water conservation
- Water monitoring and mitigation plans
- Cooperative agreements between water users
- Other states and their implementations
- Substitute water supply plans
- Annual replacement plans
- Provision of replacement water

Implementation

- Conjunctive Management is a complex and dynamic process that requires careful planning, ongoing monitoring, and adaptability to ensure the sustainable use of water resources in the face of changing environmental, economic, and social conditions.
- Collaboration among stake holders and robust regulatory frameworks are keys to its success.

Potential Implementation Approach

- DATA COLLECTION
- STAKEHOLDER ENGAGEMENT
- INTEGRATED PLANNING
- POLICY AND REGULATORY FRAMEWORK
- INFRASTRUCTURE DEVELOPMENT
- MONITORING AND DATA MANAGEMENT
- ADAPTIVE MANAGEMENT
- ENVIRONMENTAL CONSIDERATIONS
- DROUGHT PREPAREDNESS
- EVALUATION AND REPORTING

Potential Implementation Approach

NEVADA GOLD MINES

DATA COLLECTION

- Conduct a comprehensive assessment of the region’s water resources
- Collect data on water availability and actual usage

Potential Implementation Approach

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

- Involve local communities, water users, government agencies, and experts in the decision-making process
- Seek input and feedback from stakeholders to understand their needs and concerns
- Solicit feedback on groundwater models from the public

Potential Implementation Approach

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

INTEGRATED PLANNING

- Create a comprehensive water management plan that integrates surface water and groundwater resources
- Identify goals and objectives for sustainable use and management

Potential Implementation Approach

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

INTEGRATED PLANNING

POLICY AND REGULATORY FRAMEWORK

- Develop or update policies, regulations, and legal frameworks
- Ensure that regulations address water rights, allocations, and environmental protection

Potential Implementation Approach

NEVADA GOLD MINES

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

INTEGRATED PLANNING

POLICY AND REGULATORY FRAMEWORK

INFRASTRUCTURE DEVELOPMENT

- Invest in infrastructure projects as needed (ASR, augmentation, etc.) to aide in achieving set goal(s)

Potential Implementation Approach

NEVADA GOLD MINES

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

INTEGRATED PLANNING

POLICY AND REGULATORY FRAMEWORK

INFRASTRUCTURE DEVELOPMENT

MONITORING AND DATA MANAGEMENT

- Establish or enhance a robust monitoring system to track water use and water levels
- Use data to inform decision-making and adapt strategies as needed

Potential Implementation Approach

NEVADA GOLD MINES

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

INTEGRATED PLANNING

POLICY AND REGULATORY FRAMEWORK

INFRASTRUCTURE DEVELOPMENT

MONITORING AND DATA MANAGEMENT

ADAPTIVE MANAGEMENT

- Continuously evaluate the effectiveness of conjunctive management strategies
- Adjust plans and policies based on changing conditions and stakeholder feedback

Potential Implementation Approach

NEVADA GOLD MINES

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

INTEGRATED PLANNING

POLICY AND REGULATORY FRAMEWORK

INFRASTRUCTURE DEVELOPMENT

MONITORING AND DATA MANAGEMENT

ADAPTIVE MANAGEMENT

ENVIRONMENTAL CONSIDERATIONS

- Consider the impact of water management on aquatic habitats and wildlife

Potential Implementation Approach

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

INTEGRATED PLANNING

POLICY AND REGULATORY FRAMEWORK

INFRASTRUCTURE DEVELOPMENT

MONITORING AND DATA MANAGEMENT

ADAPTIVE MANAGEMENT

ENVIRONMENTAL CONSIDERATIONS

DROUGHT PREPAREDNESS

- Implement measures to ensure resilience during dry periods

Potential Implementation Approach

DATA COLLECTION

STAKEHOLDER ENGAGEMENT

INTEGRATED PLANNING

POLICY AND REGULATORY FRAMEWORK

INFRASTRUCTURE DEVELOPMENT

MONITORING AND DATA MANAGEMENT

ADAPTIVE MANAGEMENT

ENVIRONMENTAL CONSIDERATIONS

DROUGHT PREPAREDNESS

EVALUATION AND REPORTING

- Regularly assess the progress and outcomes of conjunctive management efforts
- Provide transparent reporting to stakeholders and the public

Potential Implementation Approach

- DATA COLLECTION
- STAKEHOLDER ENGAGEMENT
- INTEGRATED PLANNING
- POLICY AND REGULATORY FRAMEWORK
- INFRASTRUCTURE DEVELOPMENT
- MONITORING AND DATA MANAGEMENT
- ADAPTIVE MANAGEMENT
- ENVIRONMENTAL CONSIDERATIONS
- DROUGHT PREPAREDNESS
- EVALUATION AND REPORTING

Questions

References

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Groundwater Pumping from Distant Locations for Targeted Flow Augmentation in Humboldt River

JAY DIXON, PE, WRS

DWIGHT SMITH, PE, WRS

JOINTLY PREPARED WITH SUPPORT FROM THE FLYING M RANCH AND PERSHING COUNTY WATER CONSERVATION DISTRICT

September 26, 2023

NDWR Conjunctive Management Workshop

Outline

1. Review the Concept

2. Describe a potential example augmentation location in the Upper Humboldt Region

3. Review and Compare Augmentation Analysis Tools

Conjunctive Management:

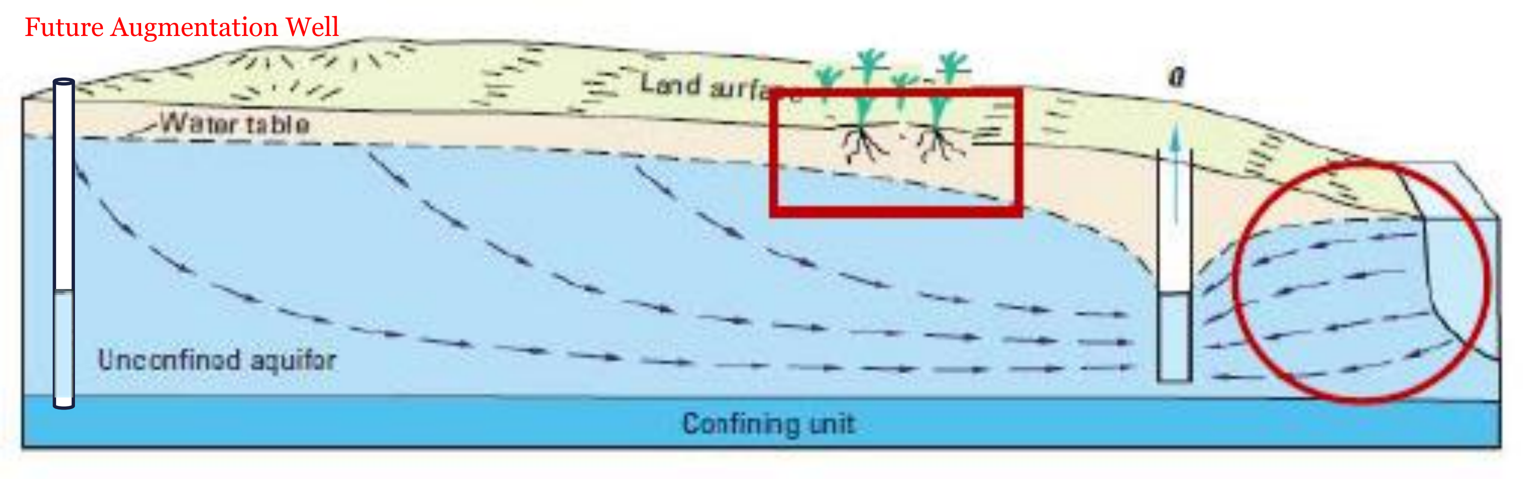
Definition:

*An adaptive process that utilizes the connection between surface water and groundwater to **maximize water use**, while minimizing impacts to streamflow, groundwater levels, and priority rights in an effort to **increase the overall water supply** of an area and **improve the reliability of that supply**.*

--- modified from Nebraska definition

NEBRASKA
Good Life. Great Water.
DEPT. OF NATURAL RESOURCES

DRILL HERE!!!



Augmentation –Location, Time, Amount

1. LOCATION: Focus on distal areas where stream capture is <10% of pumped groundwater over 50 years (areas capturing ET)

2. TIME: During times of anticipated and/or measured low stream flow. Goal is to send more water downstream without creating conflicts elsewhere. However, upstream augmentation won't be effective if existing downstream capture is not addressed.

3. AMOUNT: Pumping volume depends on location, hydrogeologic conditions, and regulatory limits.

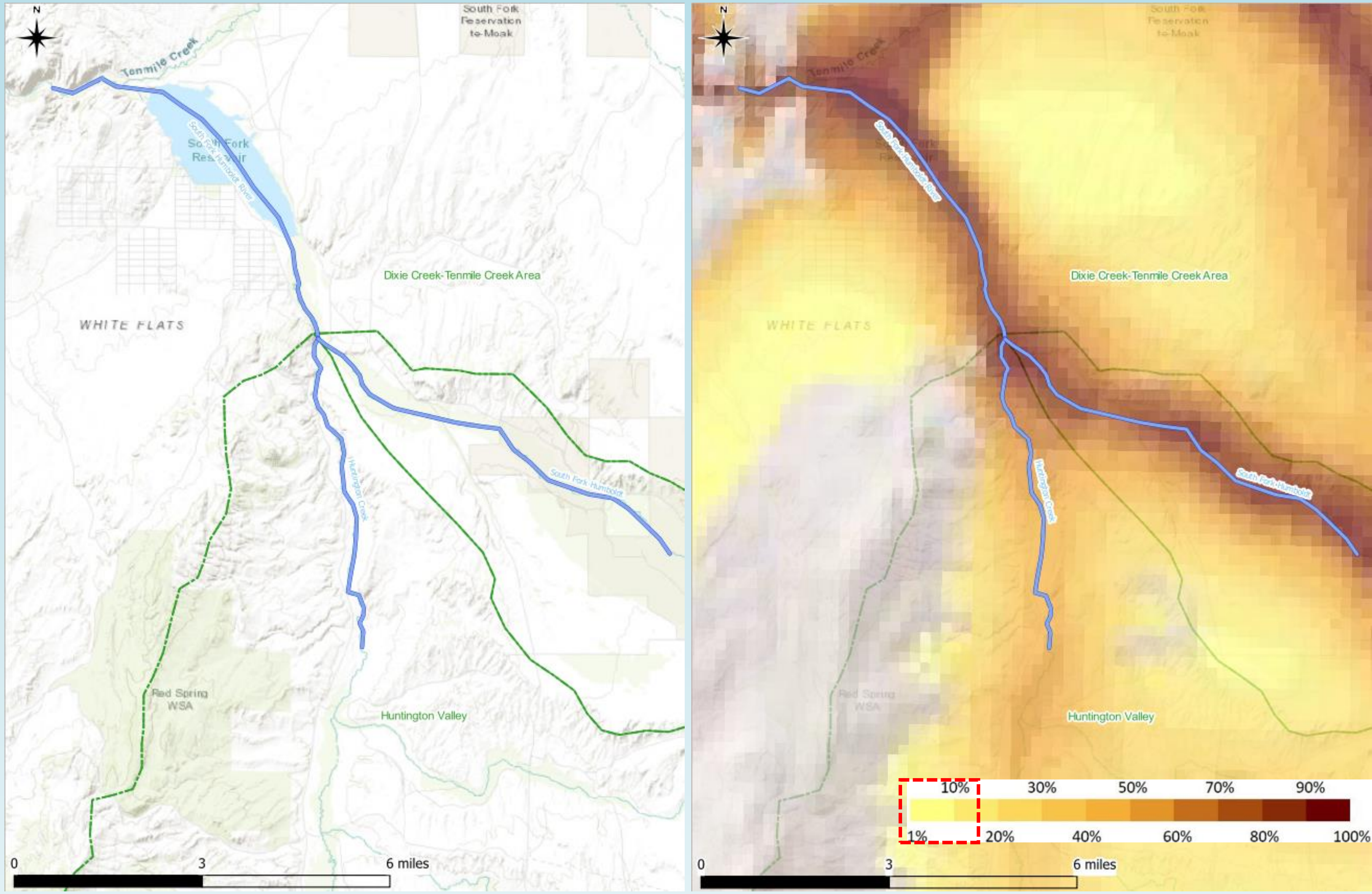
Conceptual Approach

1. Potential Augmentation Sources:
   a) Mines dewatering in excess of consumptive use demands,
   b) Existing agricultural areas distal from river with willing and/or incentivized producers converting portions of existing pumping to augmentation,
   c) Undeveloped areas within select basins that can capture a portion of the unused perennial yield and are situated near areas of phreatophytes with low environmental sensitivity (areas with uncaptured groundwater discharge)
2. Wells and water conveyance infrastructure would be permitted, funded, and constructed to deliver water directly to the Humboldt River or tributary.
3. Augmentation program water would need to be managed to deliver water to river at appropriate times (meet decreed deliveries)

Suggested Technical Approaches & Example

1. Using the NDWR Capture Models
   - Trust but verify- Analytical checks

2. Potential Augmentation Examples (Opportunities) in the Upper Humboldt Region



Bulletin 49 – Simulated stream capture map for model layer 1 after 100 years of pumping.

Capture Analysis Tools & Considerations

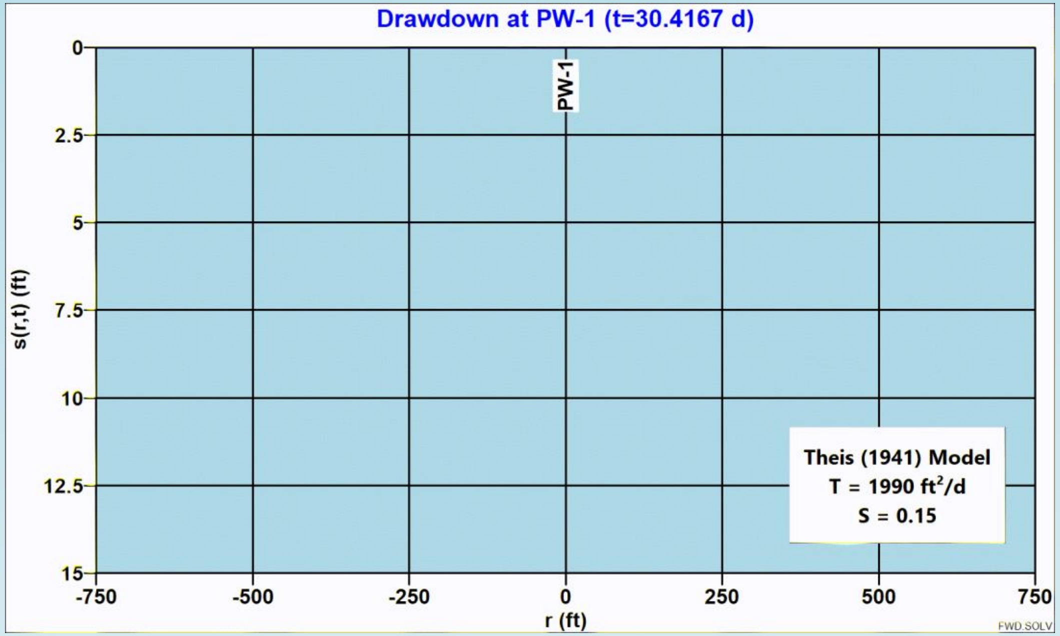
- Glover Method – analytical solution
- Stream Depletion Factors (SDF) – analytical w/ GW modeling to account for varying boundary conditions & aquifer properties
- Alluvial Water Accounting System (AWAS): http://www.ids.colostate.edu/projects.php?project=awas/awas.html Recharge_as_Augmentation_in_SP.pdf (colostate.edu) – 1994, Altenhofen, et al
- FWD:SOLV – analytical tool for predicting drawdown and stream capture from multiple wells
  - ✓ Built from AQTESOLV platform (leading aquifer test analysis platform since 1989)

Capture Analysis Considerations- FWD:SOLV

- FWD:SOLV: http://www.aqtesolv.com/fwdsolv.htm

FWD:SOLV includes many useful predictive models to assist you in the evaluation of drawdown and stream depletion impacts produced by one or more pumping wells.

- isotropic single-porosity aquifer (Theis 1935)
- sloping isotropic single-porosity aquifer (Polubarinova-Kochina 1977)
- anisotropic single-porosity aquifer (Papadopulos 1965)
- anisotropic unconfined aquifer with delayed yield (Neuman 1972)
- stream depletion (fully penetrating) (Theis 1941; Glover and Balmer 1954)
- stream depletion (slightly penetrating) (Hunt 1999)



Drawdown and Stream Depletion Models

Use ***FWD:SOLV*** to make quick forecasts of **drawdown** and **stream depletion** using a suite of analytical models for aquifers that may be infinite or bounded, isotropic or anisotropic.

Visualization and Reporting Tools

Interpret predictive modeling simulations with visualization and analysis tools (**contour**, **profile**, **time series** and **stream depletion** plots and a detailed **report**) built into ***FWD:SOLV***.

Step 3: Optimize Design Parameters

FWD:SOLV provides **high-performance optimization tools** to assist in the design of pumping rate and duration for user-specified wells. When you apply the **optimization tools**, the Results window gives you immediate visual feedback for assessing the impact of optimized design parameters.

Capture Analysis Considerations- FWD:SOLV

- Simulates variable pumping schedules
- Supports multiple pumping wells
- Supports fully and partially penetrating, linear stream boundary
- Benchmarked against AWAS

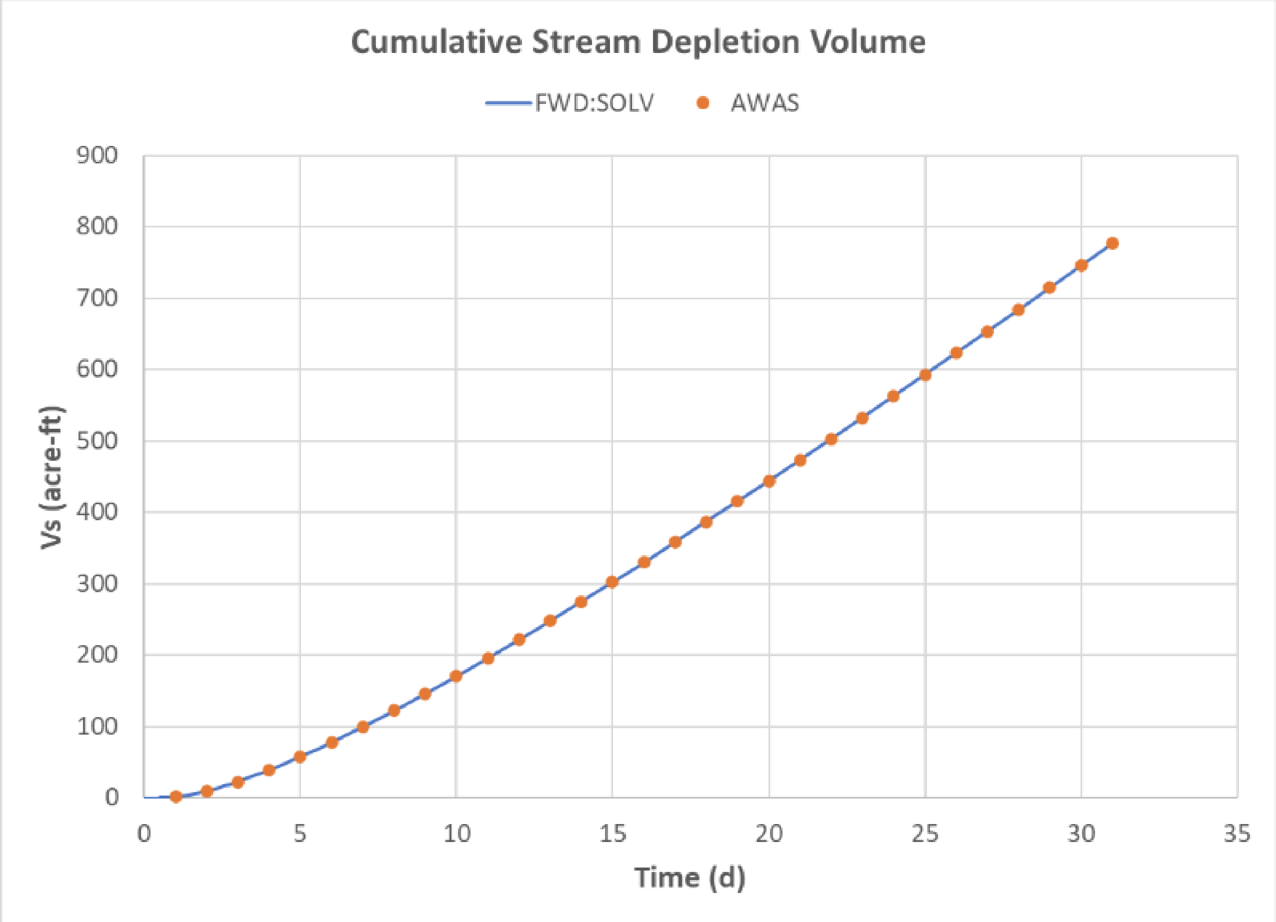


Figure B2-1. Comparison of cumulative stream depletion volume (V_S) computed by FWD:SOLV and AWAS for a pumping well near fully penetrating stream given T = 927500 gal/d/ft, Sy = 0.1, Q = 40 acre-ft/d and ℓ = 2450 ft.

Example Augmentation Opportunity

1. Project basin had ~2,000 AFA of capture (simulated) in 2016

2. Use regional capture model (Bulletin 49) to identify augmentation opportunities (<10% at 50 years)

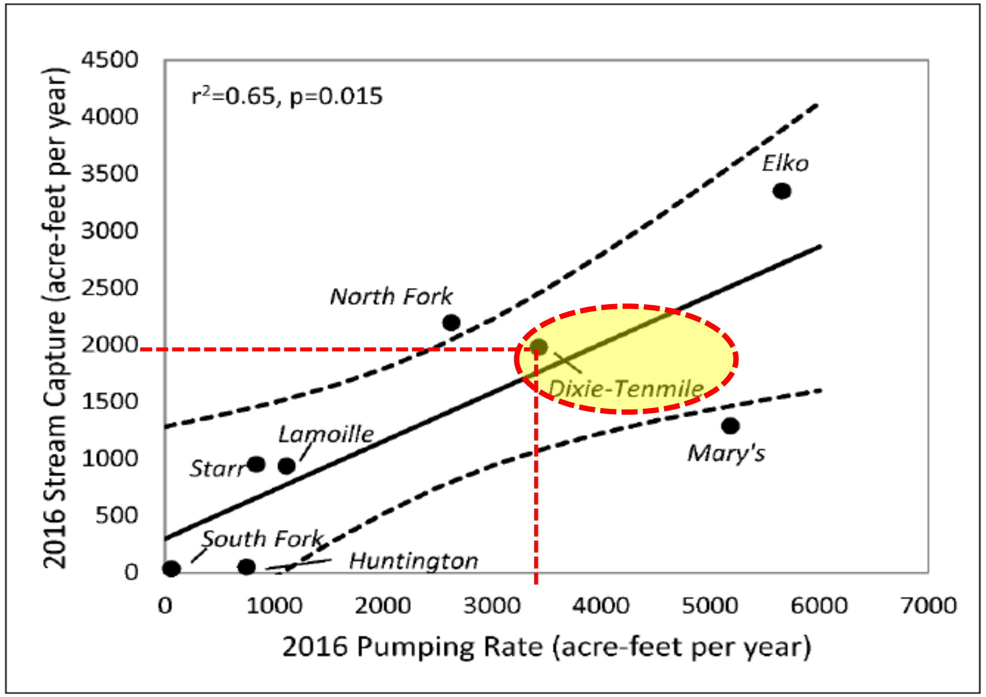
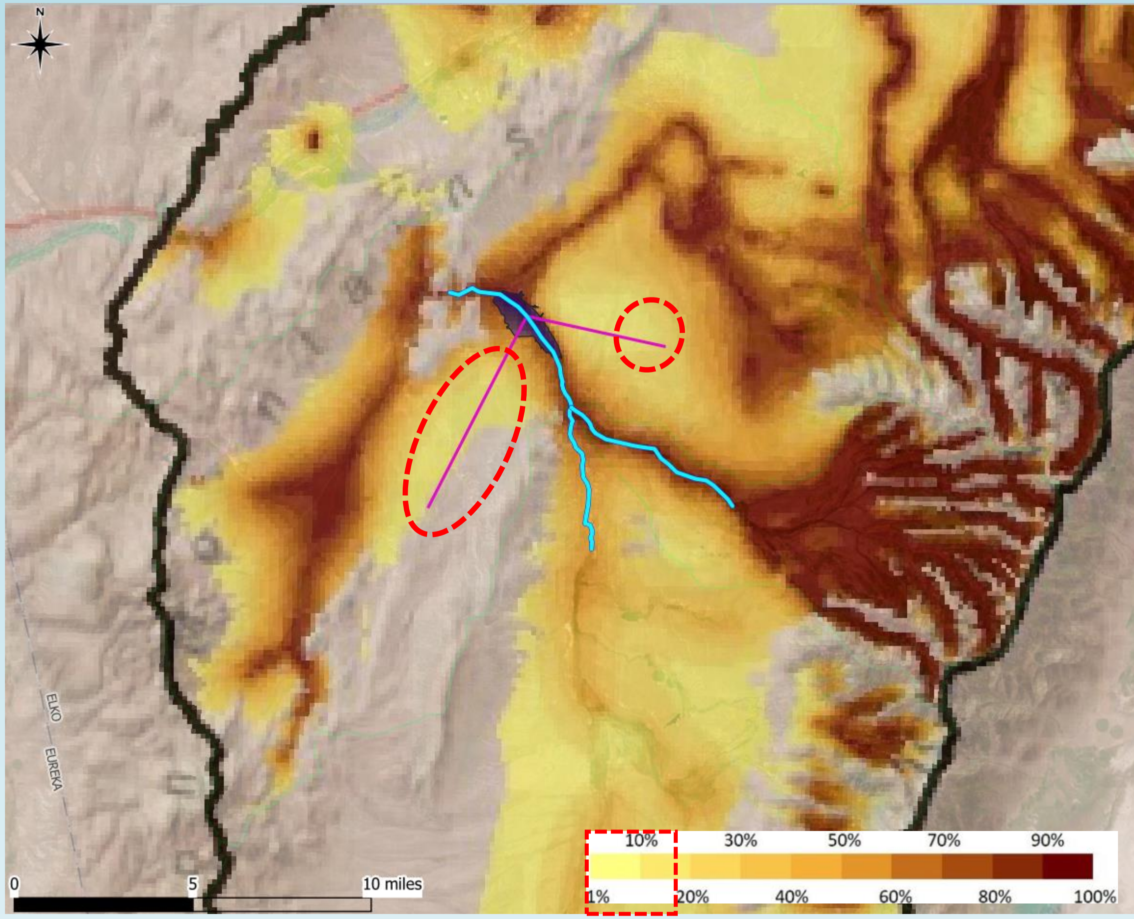


Figure 38. Linear regression comparing 2016 pumping rates to the 2016 stream capture for individual hydrographic basins. Dashed lines indicate the 95% confidence interval. Individual basins identified.

Bulletin 49



Layers 1 and 2 – projected 50-yr capture (Figs. 43 and 49, respectively).

Example Augmentation Opportunity

Project Setting and Analysis Parameters:

1. Existing surface water reservoir

2. Lithology: alluvial aquifer to the SW, sandstone to SE of reservoir
   a) Transmissivity = 750 ft^2/d based on Bulletin 49 transmissivities: ~500 (sandstone) - 1,000 (alluvium) ft^2/d
   b) Storativity = 0.1 based on Bulletin 49 storativity: ~0.03 – 0.1
   c) Stream depletion λ = 3 ft/d based on Bulletin 49 hydraulic conductivities and stream boundary properties

3. Augmentation well(s) design: 800-ft of screen

4. Target Augmentation Pumping: based on 1,000 afa using existing groundwater rights (~50% of 2016 capture)
   a) Location(s): 2 well evaluated; one site on each side of reservoir/stream
   b) Time & Amount: 6 months (Jul. – Dec.) @ 1,239 gpm or 12 months @ 619 gpm
   c) Repeat schedule for 50 years (18,250 days)
   d) Order 1329 capture criteria <10% over 50 years (stream capture must be less than 62 gpm, or 100 afa)

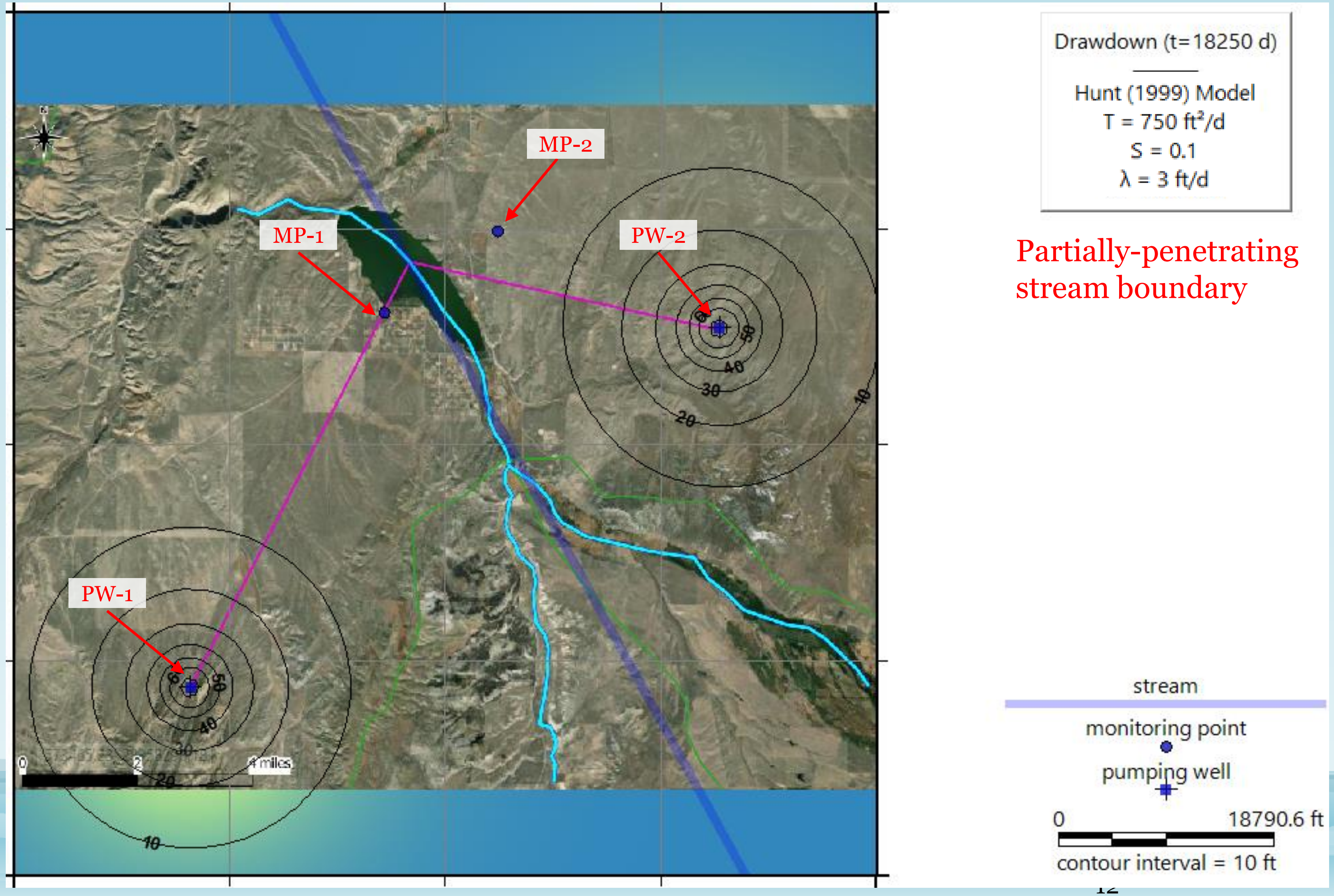
Example Augmentation Opportunity- FWD:SOLV

Using FWD:SOLV to evaluate stream capture from groundwater pumping at various with various pumping rates and times.

1. PW-1 and PW-2 each pumping @ 1,239 gpm for 6 months each year
   a) PW-1 placed 7.5 miles from stream
   b) PW-2 placed 4.4 miles from stream

2. MP-1, 2 represent (hypothetical) monitoring wells at edge of existing groundwater mound.

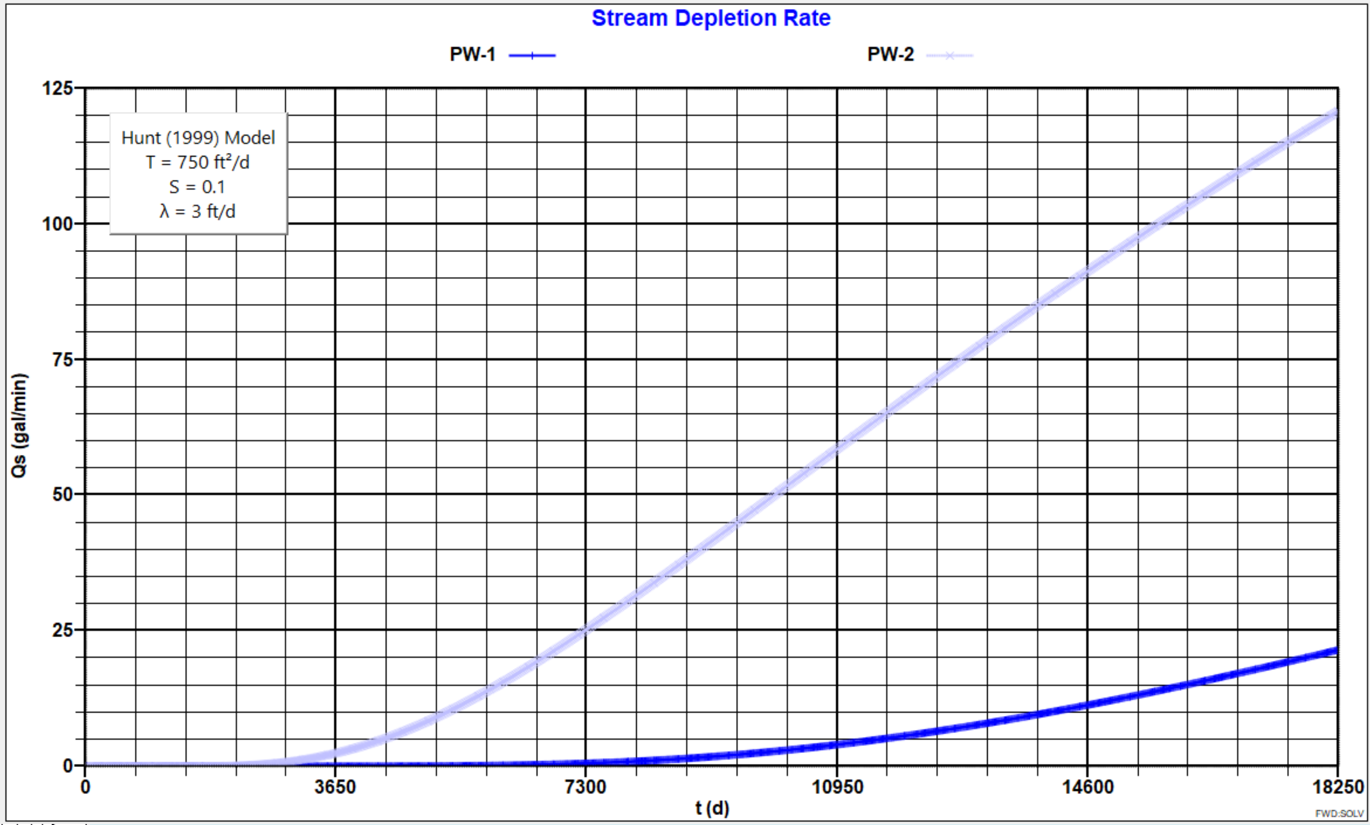
3. Partially penetrating stream

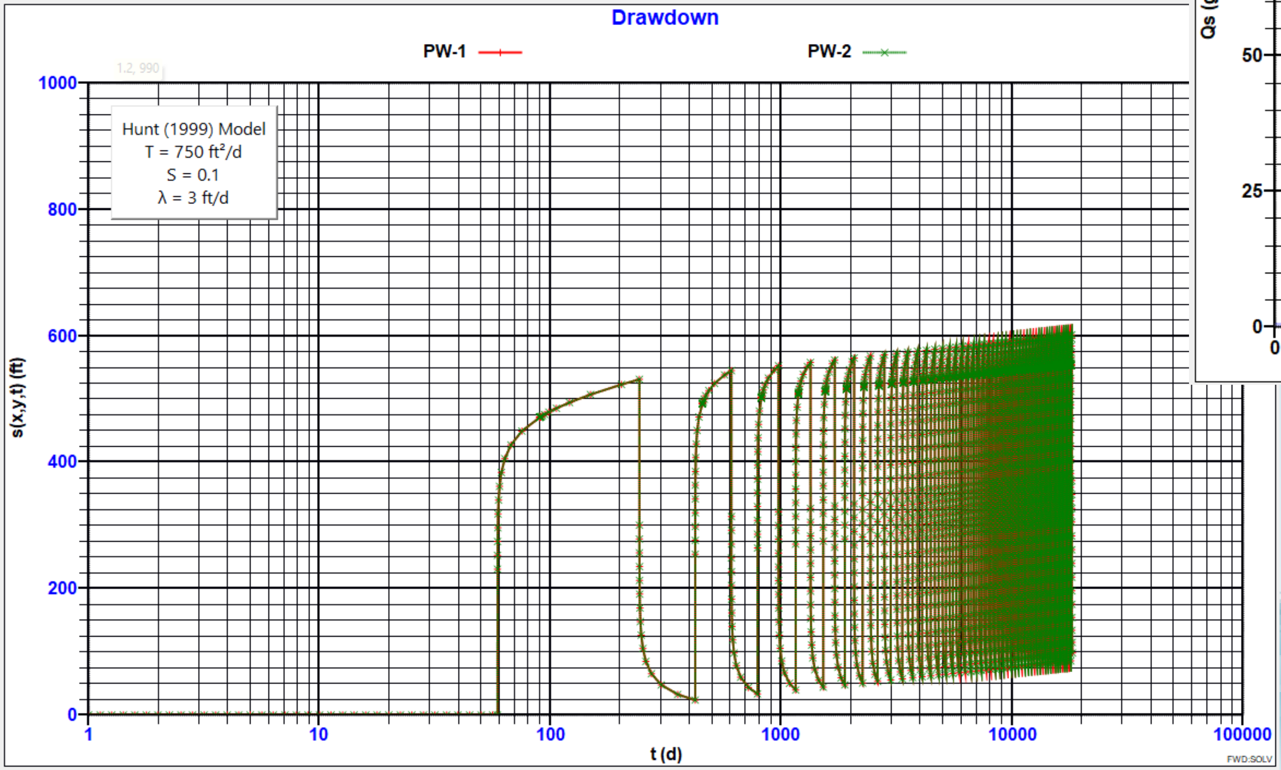


Example Augmentation Opportunity- FWD:SOLV

Results:

- Significant drawdown at pumping wells
- Insignificant drawdown near the reservoir



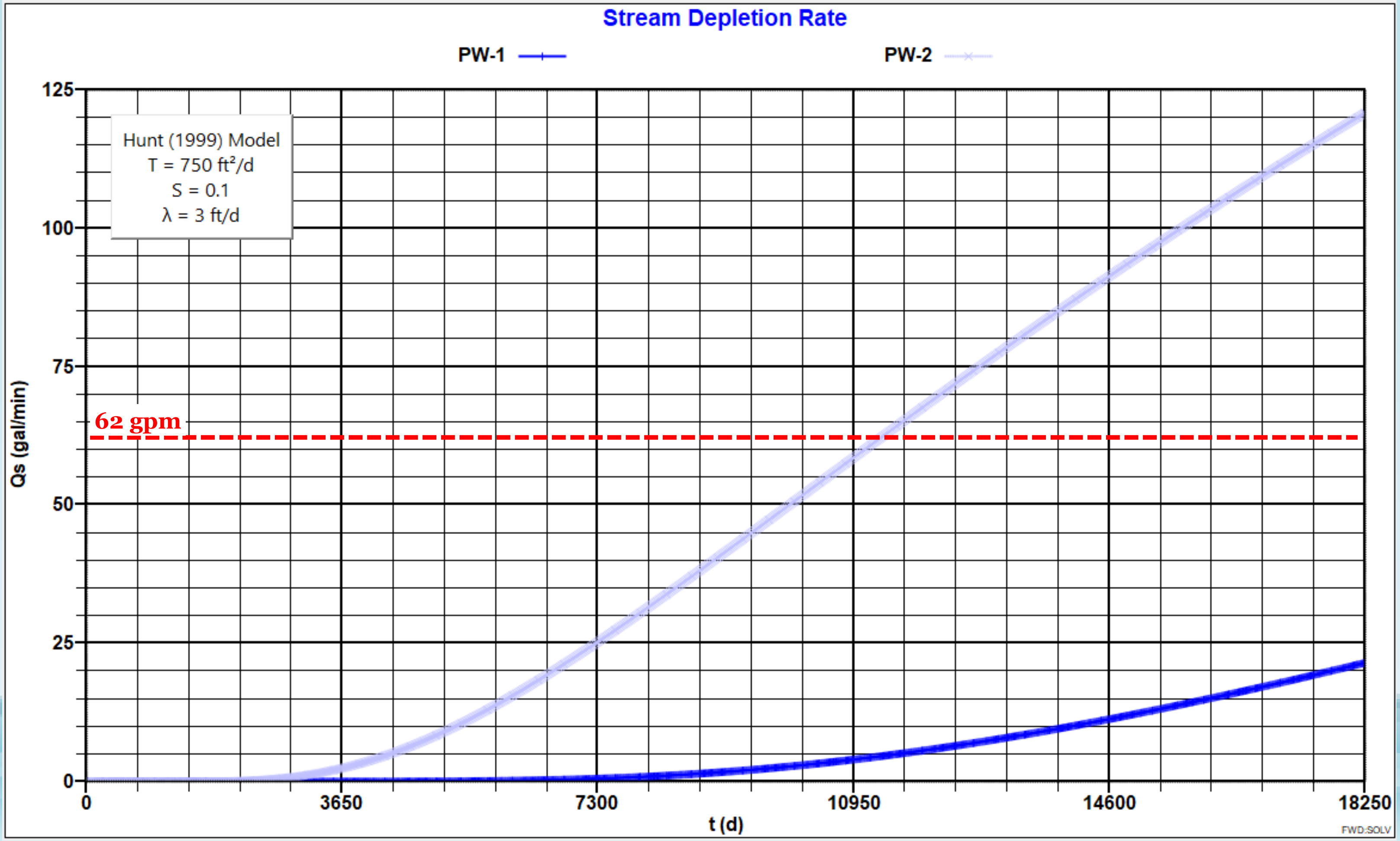


Example Augmentation Opportunity- FWD:SOLV

<u>Results:</u>

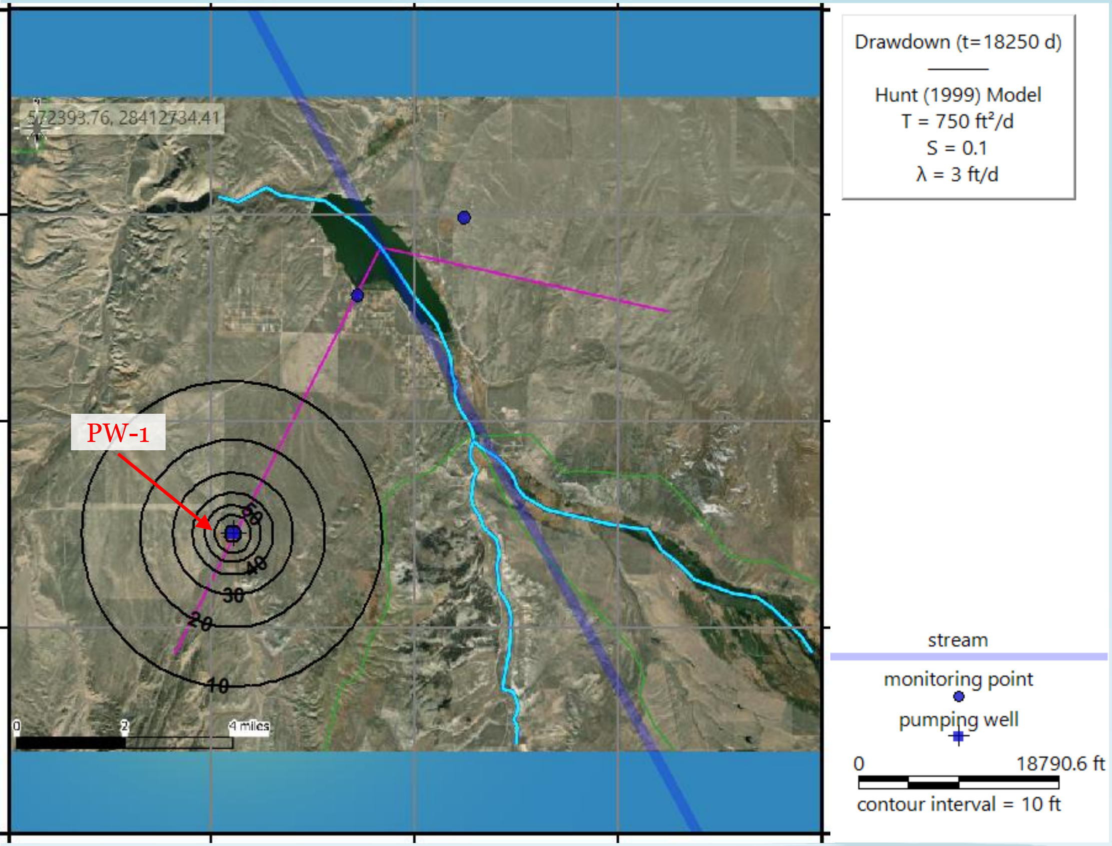
PW-1 at 7.5 miles captures 3.5% (22 gpm) from stream at 50 years of <u>seasonal pumping</u> @ 1,239 gpm

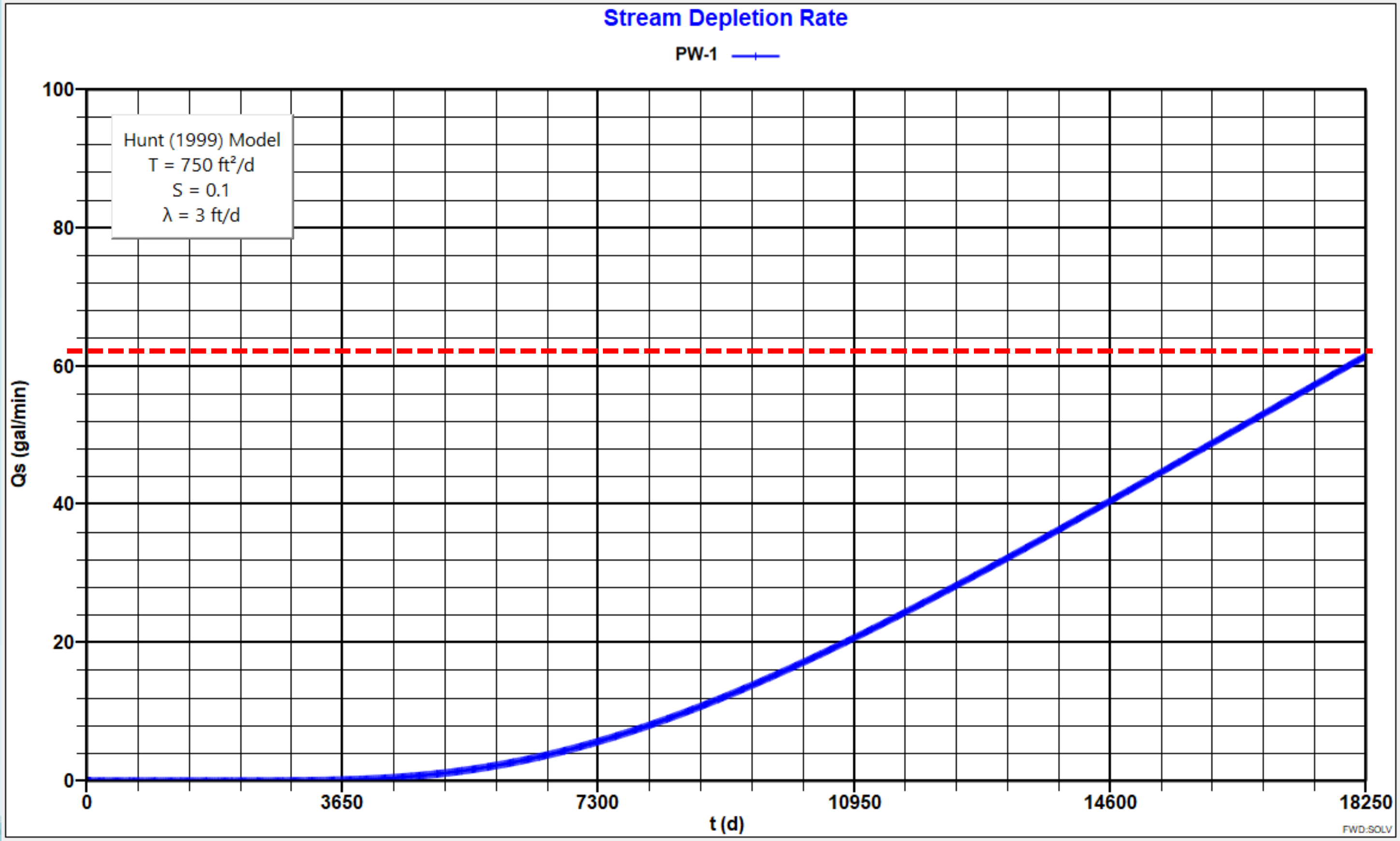
PW-2 at 4.4 miles captures 20% (121 gpm) from stream at 50 years of <u>seasonal pumping</u> @ 1,239 gpm



Example Augmentation Opportunity- FWD:SOLV

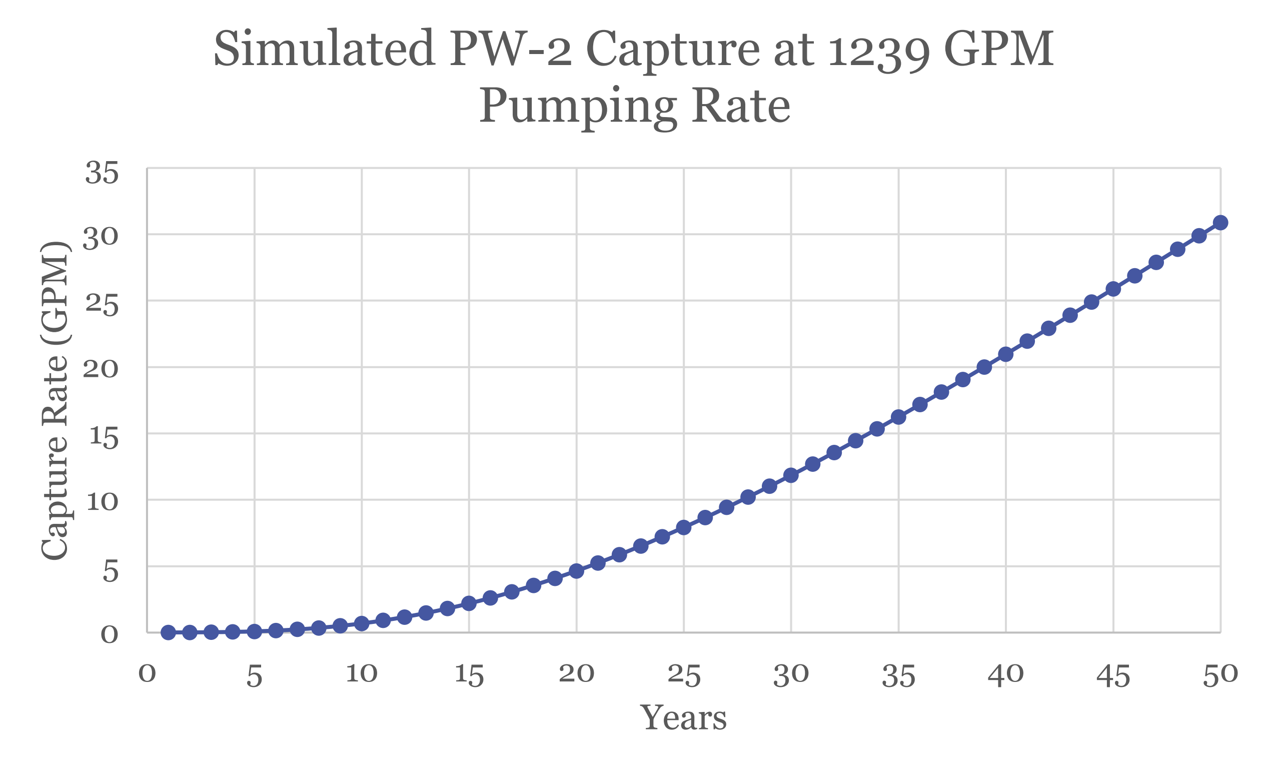
How close can PW-1 be to the stream? Answer: ~4.5 miles





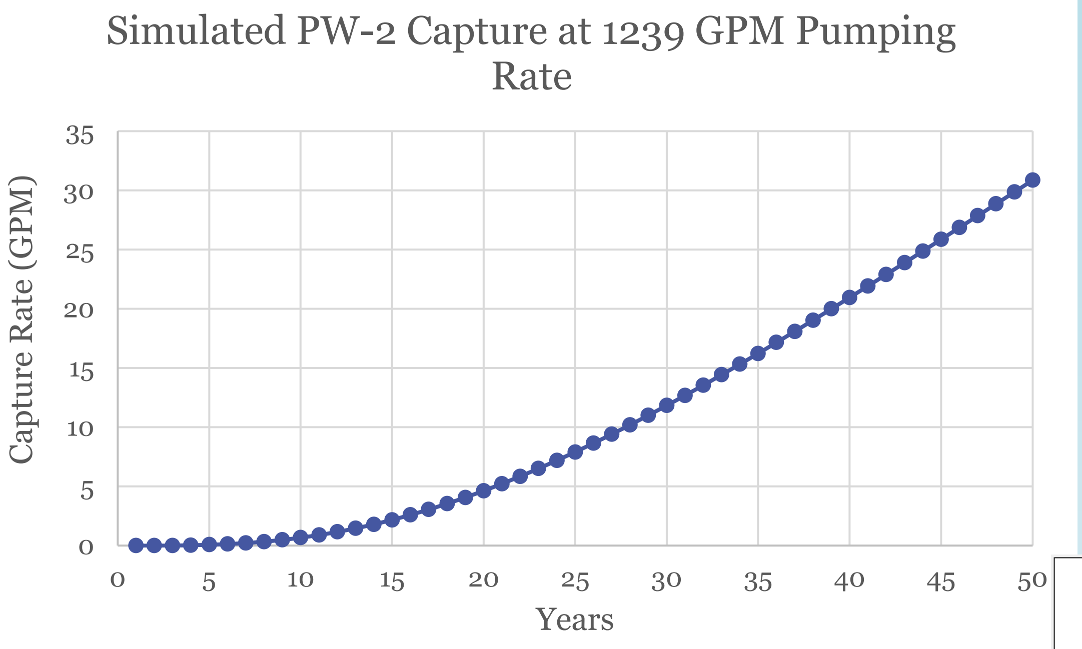
Preliminary Capture Model Results

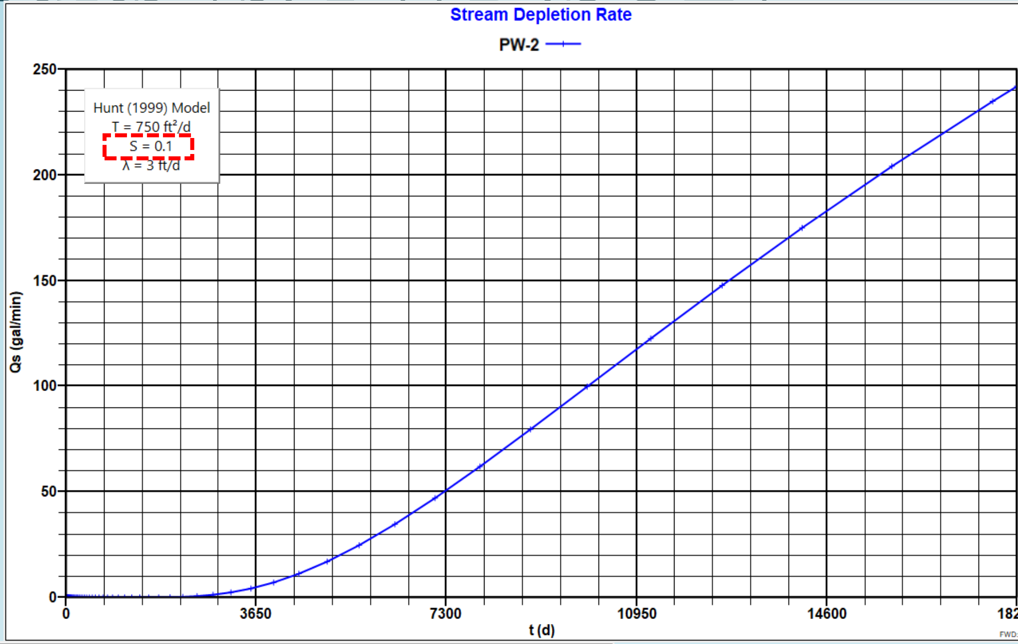
- Carroll et al 2023, NDWR Bulletin 49
- Location for capture assessment is simulated flow in the Humboldt River just down-stream of South Fork Reservoir.
- PW-1 at 1239 gpm and 4.5 miles distance reaches 0.8% capture at 50 years (10 gpm river capture)
- PW-2 at 1239 gpm and 4.4 miles distance reaches 2.5% capture at 50 years (31 gpm river flow capture)

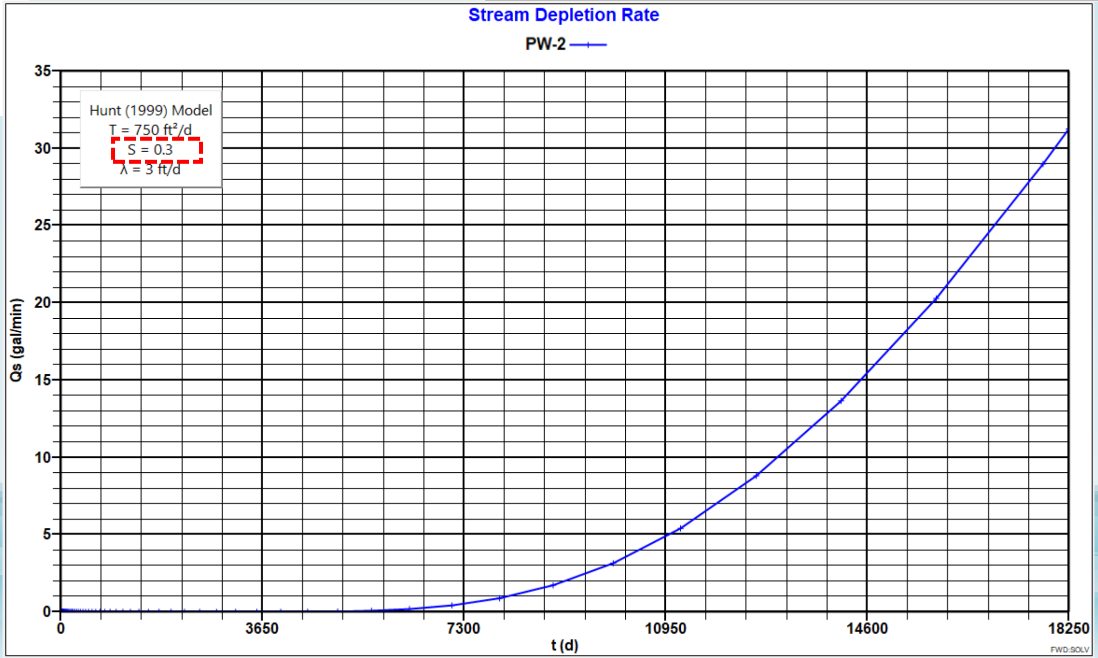


Preliminary Capture Model Results vs. FWD:SOLV

Bulletin 49 Model







FWD:SOLV Analysis

FWD:SOLV capture matches the model with a high storage value of 0.3 (not realistic)

Upper Humboldt River Model Limitations

- South Fork Reservoir not explicitly represented in the model.
- Runs on annual stress periods, cannot simulate monthly or seasonal pumping effects that might be associated with an augmentation project.
- Average annual capture – does not consider seasonal capture as a percent of flow.
- Model uses a river flow simulation module that does not allow for representation of direct input of flow into the river – cannot be directly used to assess augmentation water losses in flow as conveyed downstream.
- Middle Humboldt River Model is needed to simulate potential conveyance down to the lower basin.

Opportunities for Humboldt River Flow Augmentation – Mine Dewatering

- Reprioritize temporary mine dewatering water uses
  - Priority: use to offset mining and milling water demands
  - ➢ Second priority: convey and discharge to the Humboldt River or a perennial tributary
  - Third priority: return to aquifer via RIBs
  - Last priority: offset some other type of consumptive use in the basin (agriculture, power, etc.)
- Post-mining augmentation strategy if capture of river flow persists after dewatering activities. Possibly some credit for mining-period augmentation achieved.

Note: Discharge to river subject to suitability of water quality

Identify Augmentation Opportunity Areas

- Determine Opportunity Areas
  - Proximity to tributary stream or river
  - Locations that can be pumped without conflict to existing water rights
  - Hydrographic basins with unappropriated and/or unused water available
  - Large ET areas not along riparian corridors could be exploited to lessen overall long-term pumping impacts

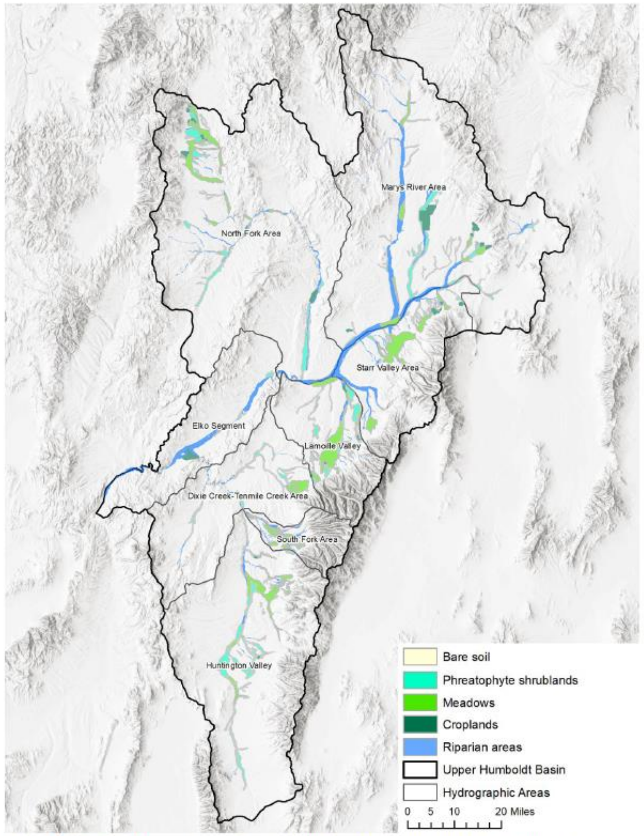
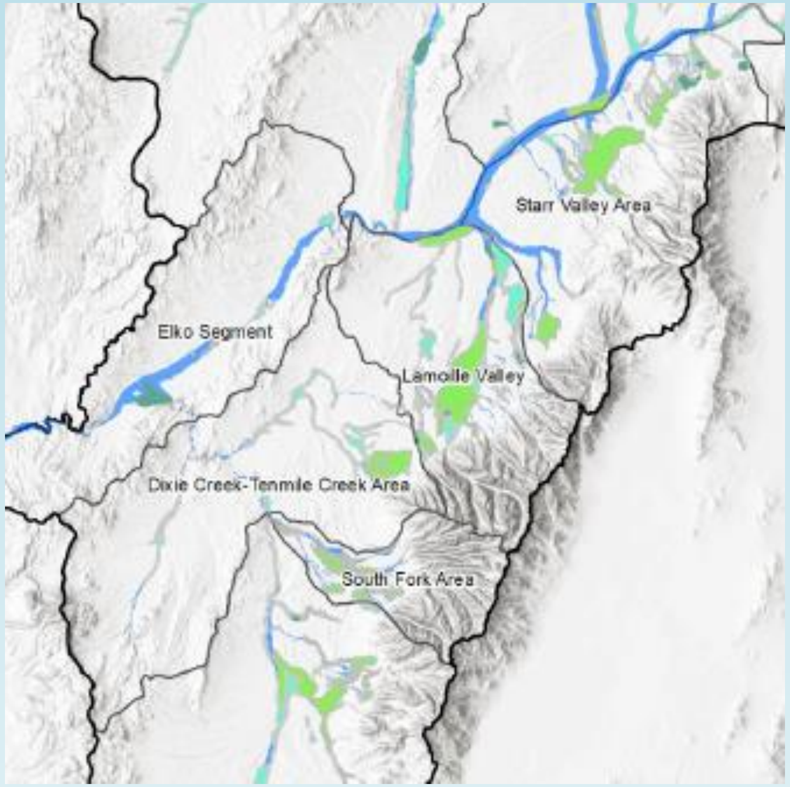


Figure 6c. Potential areas of groundwater discharge and classified ET Units for the upper Humboldt River Basin.



Huntington et al, 2022, Bulletin 48

Closing Thoughts – Augmentation Concept

- Groundwater pumping near the river is the problem.
- But groundwater pumping at locations more distant from the river in a strategic flow delivery to the river to help satisfy downstream decreed water rights could be a part of the solution.
- Augmentation water development locations require careful review and short-term gain in flows need to heavily out way long-term degradation of flows (long-term capture percentage needs to be low).
- Augmentation water needs to be able to make it down to the lower basin - conveyance of augmentation water downstream needs further assessment, and likely will require additional actions in Middle Humboldt losing reaches, where augmentation would have more impact.

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Funding Schemes for Water Master, River Management, and Gaging

Caitlin Skulan

September 26, 2023

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Presentation Roadmap

- Adjudicated River Funding Schemes
  - Walker River
    - Authority for Funding
    - Source of Funding
    - Budget
  - Truckee Rivers
    - Authority for Funding
    - Source of Funding
    - Budget
- Humboldt River Funding Considerations
- Questions?

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Adjudicated River Funding

- Federal Adjudications
  - Developed Under Decree
  - Cover Multiple Jurisdictions

- State Adjudications
  - Statutory Authority
  - *NRS 533.280:* Annual Budget for Stream System or Water District; Contents, Limitations on Assessments

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Walker River

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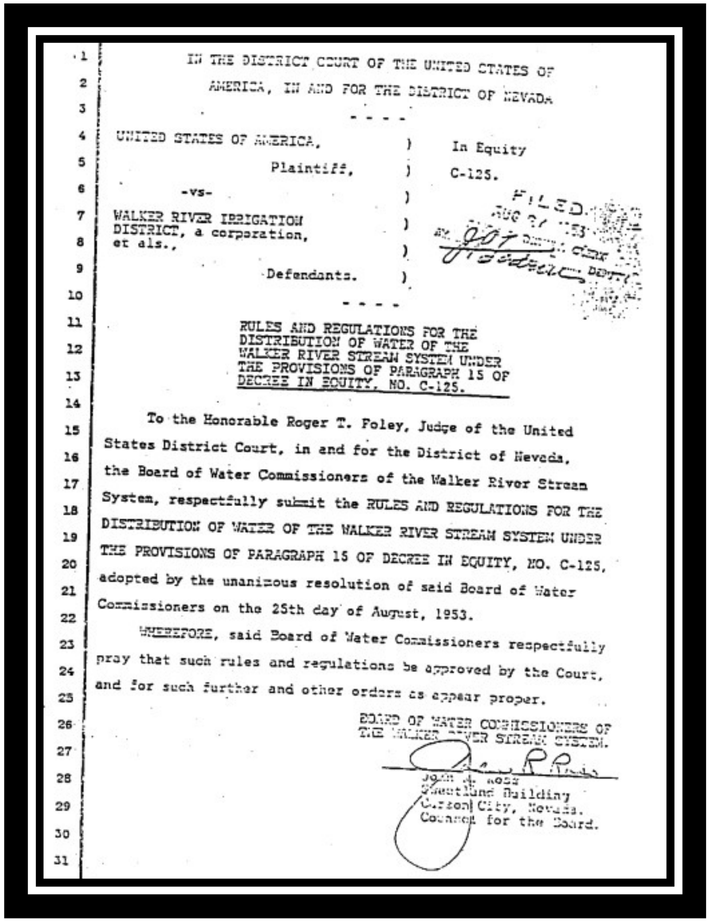
Authority for Walker River Funding

- 1936 Walker River Decree;
- 1953 Rules and Regulations of Distribution;
- Subsequent Modifications
- Petition to Court, Objections, and Hearing



IN THE DISTRICT COURT OF THE UNITED STATES OF AMERICA, IN AND FOR THE DISTRICT OF NEVADA

- - - -

UNITED STATES OF AMERICA, Plaintiff, -vs- WALKER RIVER IRRIGATION DISTRICT, a corporation, et als., Defendants.	In Equity C-125.

FILED

- - - -

RULES AND REGULATIONS FOR THE DISTRIBUTION OF WATER OF THE WALKER RIVER STREAM SYSTEM UNDER THE PROVISIONS OF PARAGRAPH 15 OF DECREE IN EQUITY, NO. C-125.

To the Honorable Roger T. Foley, Judge of the United States District Court, in and for the District of Nevada, the Board of Water Commissioners of the Walker River Stream System, respectfully submit the RULES AND REGULATIONS FOR THE DISTRIBUTION OF WATER OF THE WALKER RIVER STREAM SYSTEM UNDER THE PROVISIONS OF PARAGRAPH 15 OF DECREE IN EQUITY, NO. C-125, adopted by the unanimous resolution of said Board of Water Commissioners on the 25th day of August, 1953.

WHEREFORE, said Board of Water Commissioners respectfully pray that such rules and regulations be approved by the Court, and for such further and other orders as appear proper.

BOARD OF WATER COMMISSIONERS OF THE WALKER RIVER STREAM SYSTEM.

Sweetland Building
Carson City, Nevada.
Counsel for the Board.

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Source of Walker River Funding

- Assessments-Surface Water Users
- Collected by U.S. Board of Water Commissioners & Walker River Irrigation District
- Determined Annually
  - Based on Acreage

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2023-2024 Walker River Budget

Line Item Examples

- Assessment Rate: $3.50/assessed acre
- Water Master Salary: $98,280.00
- River Rider Salaries: $58,968.00
- Gaging Expenses: $145,000.00
- Legal/Professional: $60,000.00
- **Total Operating Expenses: $509,498.00**

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Walker River Management

- Funds from Assessments used for "Daily Operating Procedures"
- Daily Meeting with Water Master and River Riders (5)
  - Discussion and decision on next day water deliveries
  - Based on priority and real time gaging data

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Truckee River

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Truckee River Funding

Authority

- Truckee River Decree
  - Subsequent Orders of the Decree Court

Source

- Court Ordered Assessment
  - $600,000 – Feb. 28, 2023
  - One-third paid each by U.S., Truckee Meadows Water Authority, and other users

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Truckee River Budget
Line Item Examples

- Salaries and Benefits: $445,997.00
- Depreciation Expense: $18,282.00
- Gaging, Field and Telemetry: $9,660.00
- Office and Mapping: $6,180.00
- Legal/Audit Fees: $28,300.00
- **Total Operating Expenses: $616,660.00**

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Funding Considerations for Humboldt River Budget and Assessment

- Funding Source
  - Limitations by Statute
  - Assessments Against GW Users?
- Budget Considerations
  - Additional Water Master Staff/River Riders
  - Additional Gaging
  - Daily Determination of Next-Day Deliveries

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counsel@water-law.com
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Exhibit "A"

In Equity 3:73-cv-0003-MMD
U.S. District Court Water Master - Chad J Blanchard
Truckee River and Tributaries

Budgeted
Statements of Revenues, Expenses and Retained Earnings
Fiscal Year ending September 30, 2023
GENERAL FUND

Budgeted Operating Revenue	
Regular Assessment Income	$530,000
Transfer Income (Excess Payments Fund)	$70,000
Total Budgeted Operating Revenue	**$600,000**
Budgeted Operating Expenses	
Salaries & Benefits	$445,997
Payroll Taxes & Employer's Insurance	$22,675
Depreciation Expense	$18,282
Gaging, Field & Telemetry	$9,660
Indemnity Bond	$450
Insurance	$6,488
Legal & Audit Fees	28,300
Office & Mapping Expenses	$6,180
Professional Fees	3,600
Rent & Storage Expense	$54,767
Telephone	$3,360
Travel & Auto	$16,900
Total Budgeted Operating Expenses	**$616,660**
Budgeted Net Income (Loss)	**-$16,660**
Item Not Affecting Working Capital (Depreciation)	$18,282
Total Budgeted Working Capital Provided	**$1,622**
Working Capital Applied To Budgeted Equipment Acquisitions	-$1,200
Budgeted Increase (Decrease) in Working Capital	**$422**

U.S. Board of Water Commissioners - Walker River System

Prepared by: Joanne Sarkisian

ADOPTED: 3/17/2023

Budget Statements of Revenue, Expenses, and Changes in Working Capital
Year Ending June 30, 2023

Acreage Basis: 132,232 **Assessment Rate:** $3.50

		Actual 7/1 - 12/31 2022	Estimate 1/1 - 6/30 2023	Expected Total 2022-2023	Budget Amount 2022-2023	Budget Amount 2023-2024
1	**Operating Revenues:**					
2	WRID Coll. Assess. Rec.	$ 88,618	$ 184,814	273,432	273,432	281,473
3	WRID As. Rec. 1 Yr. Del.	0		0		0
4	WRID As. Rec. 2 Yr. Del.	0	0	0		0
5	USB Coll. Assess Rec.	125,161	50,997	176,158	176,158	181,339
6	USB As. Rec. 1 Yr. Del.	920	0	920		0
7	USB As. Rec. 2 Yr. Del.	0	0	0		0
8	**Total Operating Revenues:**	$ 214,699	$ 235,811	$ 450,510	$ 449,590	$ 462,812
9	**Operating Expenses:**					
10	W.M. Salary	$ 45,500	$ 45,500	$ 91,000	$91,000	$ 98,280
11	Office Salary			0	0	0
12	RR Salaries	25,130	25,130	50,260	54,600	58,968
13	SS & Medicare	5,403	5,403	10,806	13,000	13,000
14	Industrial Ins. (EICN)	502	2,500	3,002	5,000	5,000
15	Unemployment Insurance	151	1,849	2,000	2,000	2,000
16	Group Insurance	9,713	9,853	19,566	25,000	25,000
17	Pension Plan	6,393	6,393	12,786	17,500	13,800
18	Commissioners' Exp.	163	837	1,000	1,000	1,000
19	Rent	9,000	9,000	18,000	18,000	18,000
20	Fuel Expense	6,040	9,000	15,040	20,000	20,000
21	Repairs & Maint.	821	2,179	3,000	3,000	3,000
22	Supplies	121	194	1,000	1,000	1,000
23	Utilities			0	0	0
24	Telephone	2,973	3,000	5,979	6,500	6,500
25	Gaging Expense	14,472	100,528	115,000	115,000	145,000
26	Office Expense	685	0	685	0	1,000
27	Computer Expense	216	2,284	2,500	2,500	2,500
28	Travel - RR Mileage	7,057	7,500	14,557	12,000	15,000
29	Travel - Conf & Mtgs	0	1,500	1,500	1,500	1,500
30	Dues & Subscriptions	0	750	750	750	750
31	Legal/Professional	21,990	53,010	75,000	75,000	60,000
32	Accounting/Audit Exp.	6,000	0	6,000	6,000	6,000
33	Insurance	5,684	0	5,684	7,000	7,000
34	Auto Licenses & Tax	0	200	200	200	200
35	Misc. Expense	0	5,000	5,000	5,000	5,000
36	**Total Operating Expenses:**	$ 168,014	$ 291,610	$ 459,624	$482,550	$509,498

ABSTRACT SUBMISSION
August 1, 2023 Humboldt Conjunctive Management Stakeholder Meeting

Updated Conjunctive Management "White Paper" Submission

Caitlin R. Skulan
Schroeder Law Offices, P.C.
10615 Double R. Blvd. Ste 100, Reno, NV 89521
775-786-8800; counsel@water-law.com

In August 2014, Schroeder Law Offices and the Pershing County Water Conservation District ("PCWCD") authored and provided to the NDWR a "White Paper" surveying how other prior appropriation states were then implementing conjunctive management. This paper was entitled "*Water Management in a Prior Appropriation System: Conjunctive Management Solutions to Groundwater Withdrawals Effecting Surface Water Flows within the Humboldt River Basin.*" The State systems addressed in the White Paper included those in Colorado, Idaho, Utah, Washington, and Oregon.

Schroeder Law Offices is offering to review and update the White Paper and provide current information to the State Engineer in this regard. This may provide insight to other State's conjunctive management schemes, including how they have been implemented and/or updated since the original White Paper's authoring in 2014.

A paper and/or presentation may focus on other states' approaches that may benefit or be of use to Nevada.

RCI
Resource Concepts Inc

RECEIVED
2023 JUL 14 PM 4:55
STATE ENGINEERS OFFICE

July 14, 2023

Mr. Adam Sullivan, P.E.
State Engineer
Nevada Division of Water Resources
901 S. Stewart Street, Suite 2002
Carson City, Nevada 89701

RE: Conjunctive Use Management Strategies for the Humboldt River Region Request for Abstracts

Dear Mr. Sullivan:

Resource Concepts, Inc. (RC) provides the following comments regarding Conjunctive Use Management Strategies for the Humboldt River Region request for abstracts. These comments provide a brief summary of different ideas in which the State Engineer may consider when managing the Humboldt River Region conjunctively.

One area suggested for investigation would be to research and develop water flow probabilities for the different river segments which could be used to classify the times during which the pumping of a smaller (say 50-acre feet of less) groundwater source would be overshadowed by the river conditions. If surface water was not reaching the lower segment of the river, there would not be an immediate flow impact downstream, and any impact on storage would be offset by future higher flow events which would replenish small amounts of storage, offsetting smaller uses. For higher flow periods the small impact on storage or flows would potentially be orders of magnitude less than the impact of the groundwater diversion.

These conditions could be more locally bracketed by reach or segment. The Humboldt River system provides a somewhat equivalent example in the way surface waters are distributed when flows are lower and do not reach or only small amounts reach the lower portions of the basin. Although lower areas may have an earlier priority, water left in the upper reaches of the river to serve lower reaches will be highly diminished or even completely lost if left to travel down the system. This surface water management tool actually serves later, upstream priorities with water that would be lost to the system for all decreed users if a rigid, absolute priority delivery process were practiced. This management approach represents a practical, resource-based way of achieving the greatest system beneficial use in water delivery operations.

RCI requests that prior to the implementation of a conjunctive use management strategy, additional studies need to be concluded and evaluated. Currently, the Humboldt River Regional Model and Capture Tool is not yet completed and the reevaluation of the perennial yields of the Hydrographic Basins is just beginning. There should be a fuller understanding of sources, what is available and how they interact (e.g., connected tributary sources and impacts from mountain locations) prior to the implementation of a conjunctive use management strategy in the Humboldt River Region.

RCI appreciates the State Engineer's consideration of these comments and attention to this matter. If there are any questions or additional inquires of Resource Concepts, Inc. please contact our office at 775-883-1600.

Respectfully

Bruce R. Scott, P.E., WRS
Shannon McDaniel, P.E. WRS

Discussion of Market-Based Approaches to Conjunctive Management in the Humboldt River Basin

Michael H. Taylor, Ph.D.
University of Nevada, Reno

NDWR Stakeholder Workshop

26 September 2023

University of Nevada, Reno

Previous Work

- Water Valuation Study: 2019-2020
  - Provide estimates of the value of water that surface water users do not receive due to interference from groundwater pumping upstream
- Approach
  - Develop economic models to represent typical cow-calf ranching and alfalfa hay operations in the Humboldt River region that use water for irrigation
  - Parameters chosen through consultation with farmers and ranchers
  - Use models to calculate the economic value of an acre-foot of water not received due to an unanticipated supply reduction
- Relevance for Conjunctive Management in the Humboldt
  - Estimates of the value of water could be used to set financial compensation for impacted surface water users, as well as to assess fees on groundwater pumpers within the Capture Management Zone (CMZ), i.e., the Curtailment and/or Assessment Zones

Cow-Calf Ranch: Results

Table 8. Medium Size Cow-Calf Ranch: Per-Acre-Foot Value of Water ($/Acre-Foot)

Percent Shortfall	Water Shortfall	Duration of Water Supply Reduction									
		1 Year	2 Years	3 Years	4 Years	5 Years	6 Years	7 Years	8 Years	9 Years	10 Years
0%	0 AF	$215	$214	$215	$216	$216	$216	$216	$216	$216	$216
10%	187.5 AF	$216	$216	$216	$216	$216	$216	$216	$216	$216	$216
20%	375 AF	$216	$216	$216	$216	$216	$216	$216	$216	$216	$216
30%	562.5 AF	$280	$280	$280	$280	$280	$280	$280	$280	$280	$280
40%	750 AF	$288	$282	$286	$285	$286	$286	$287	$287	$288	$288
50%	937.5 AF	$292	$292	$475	$292	$583	$605	$811	$960	$1,217	$1,524
60%	1125 AF	$1,058	$291	$662	$1,084	$1,494	$1,857	$2,516	**Shutdown**	**Shutdown**	**Shutdown**

Alfalfa Hay Farm: Results

Table 13. Per-Acre-Foot Value of Water ($/Acre-Foot)

Percent Shortfall	Water Shortfall	Duration of Water Supply Reduction									
		1 Year	2 Years	3 Years	4 Years	5 Years	6 Years	7 Years	8 Years	9 Years	10 Years
0%	0 AF	$3	$3	$3	$3	$3	$3	$3	$3	$3	$3
10%	750 AF	$3	$3	$3	$3	$3	$3	$3	$3	$3	$3
20%	1500 AF	$61	$61	$115	$145	$191	$159	$159	$156	$159	$202
30%	2250 AF	$114	$165	$237	$239	$236	$204	$201	$204	$244	$244
40%	3000 AF	$114	$237	$305	$307	$305	$270	$273	$310	$310	$310
50%	3750 AF	$163	$311	$311	$313	$308	$279	$314	$314	$314	$314
60%	4500 AF	$212	$311	$311	$313	$308	$279	$314	$314	$314	$314
70%	5250 AF	$212	$311	$311	$313	$308	$279	$314	$314	$314	$314

Are these Results Reasonable?

- Water Strategist
  - Leading trade publication for water markets in the United States
  - $165 per acre-foot is the average lease price in all western states
- West Water Research
  - Combined USGS Water Use data with USDA Ag Census data to estimate the productivity of irrigation water use
  - $166 per acre-foot for irrigation water in Nevada
- Permanent Water Right Sales in Humboldt River Basin
  - Price per acre-foot ranges between $400 and $5,200 from 2006-2019
  - Corresponds to a range of annualized value between $26 and $340 per acre-foot if future profits are discounted at 7%

Market-Based Approach

- Market-Based Approach
  - Require groundwater pumpers to offset their capture
  - Offsets can be decree rights that sufficiently “wet” during the irrigation season to offset capture
  - Offsets could also be storage credits from water banking or stream flow augmentation via groundwater outside of CMZ
- Advantages
  - Does not require participants agree on a price per acre foot of water
  - Ensures that groundwater pumpers who are using water most profitably will remain in operation
  - Less profitable groundwater rights will be retired; creates incentive to shift pumping to lower conflict wells
  - Current decree rights will become more valuable (increased demand); additional opportunity for current rights holders to sell their decree rights cannot make them any worse-off

Agreement with NDWR Approach

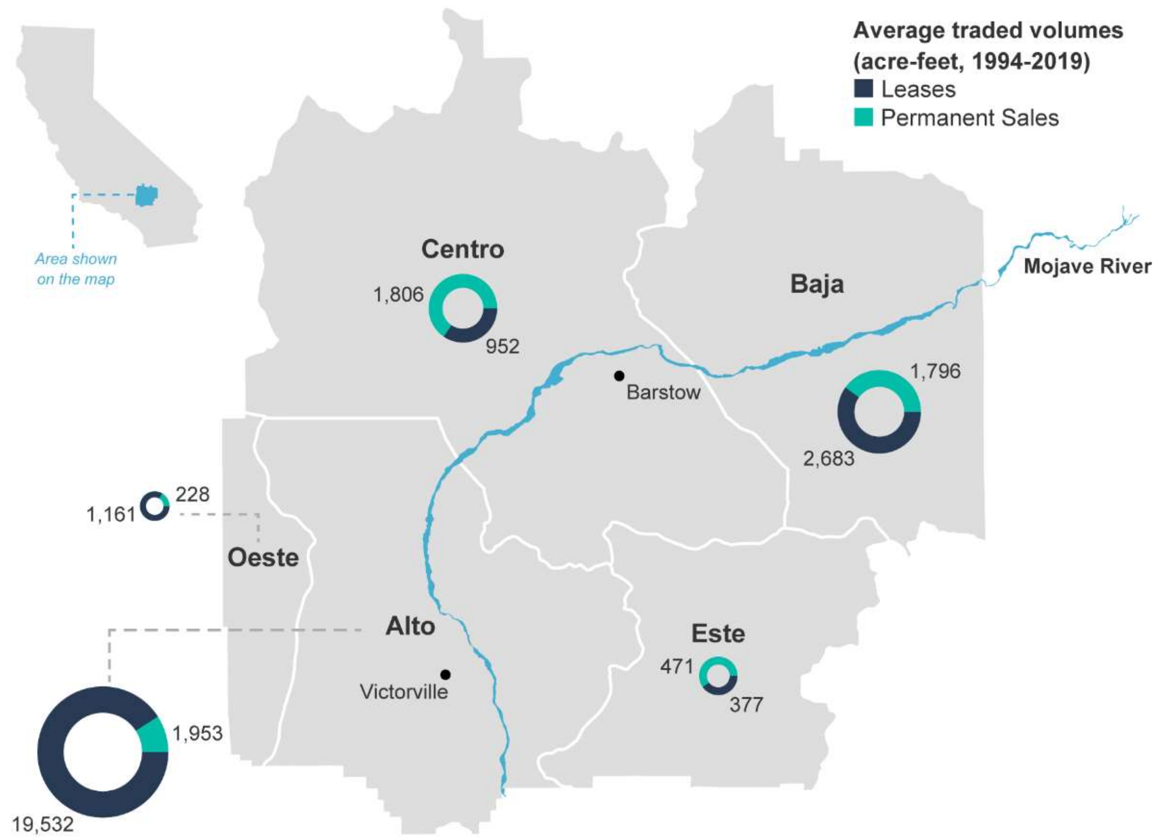
- Core Tenets of NDWR's Approach to Conjunctive Management
  - Continue to maximize beneficial use of water resources, both underground and surface water
    - Market-based approach maximizes profitable use water in basin subject to the constraint that all capture is offset to restore stream flow
  - Adhere to the Prior Appropriation Doctrine.
    - No change to prior appropriation doctrine apart provide that offsetting groundwater capture is a valid use for decree rights
  - Prevent increase in conflict from underground water rights moving into the future.
    - All future GW pumping would be required to offset capture
  - Reduce existing conflict from UG water rights.
    - Once all groundwater capture is offset, no senior surface water diverter should have their water right impacted by groundwater capture
  - While minimizing harm to the regional economy.
    - Again, approach maximizes profitable use of water
  - Through engagement with stakeholders.

Centralized versus Decentralized

- Decentralized Markets
  - Use current market institutions to coordinate purchase of decree rights for offsets
  - Water brokers coordinate sales between willing buyers and sellers
  - Issues include (i) lack of price transparency and (ii) high transaction costs potentially discouraging trades
- Centralized Market
  - Sellers indicate their minimum willingness-to-accept (WTA) price for decree rights they are willing to sell
  - Buyers indicate their maximum willingness-to-pay (WTP) price and volume demanded for decree rights
  - All rights for which WTP > WTA (+transaction costs) are transacted at the equilibrium price
  - All sellers receive > WTA
  - All buyers pay < WTP

Mojave Water Market

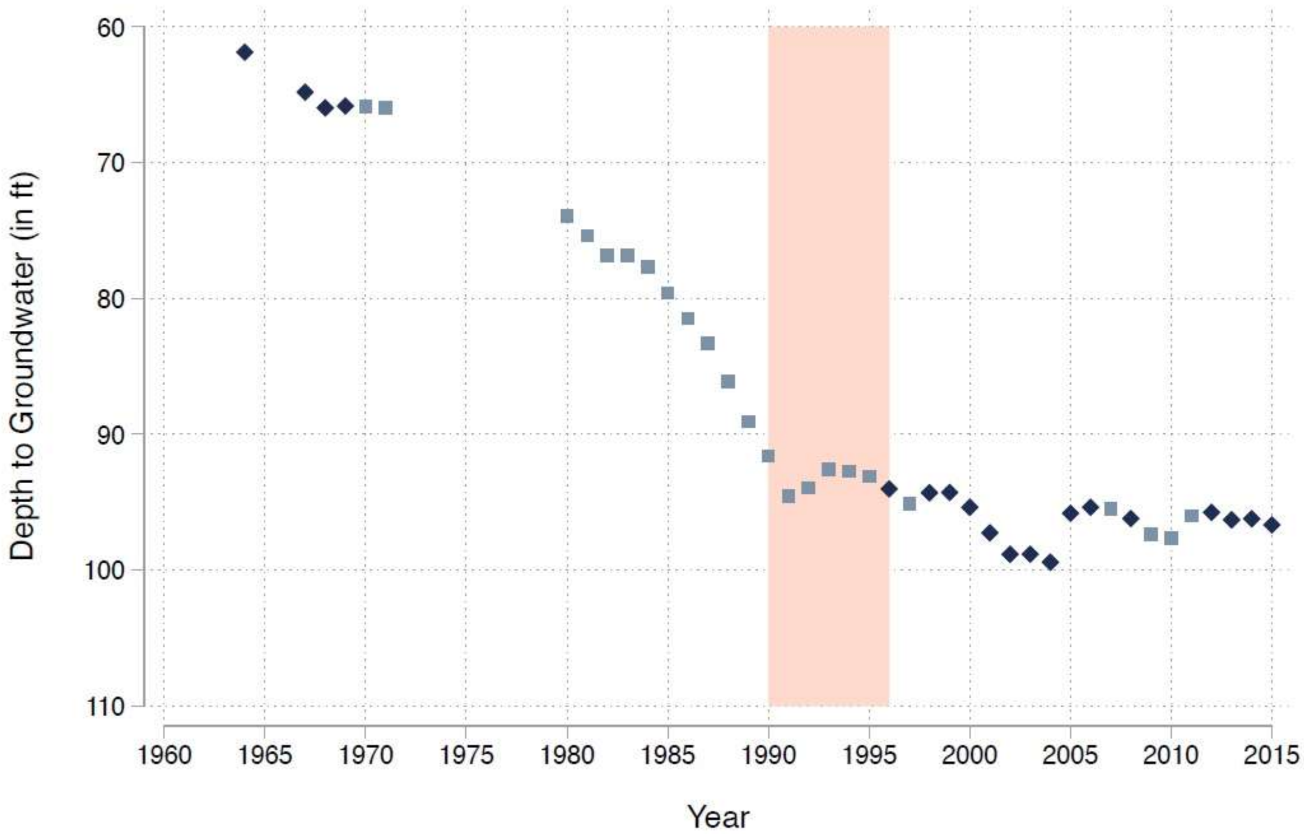
- Mojave Desert
  - Driest in N America
- Persistent overdraft from 1940s onward
- Rights system (90s)
  - Annual ramp-down
  - Subareas
- Trading: Agriculture, urban, environment



Work by Dr. Andrew Ayers, Dept. of Economics, University of Nevada, Reno

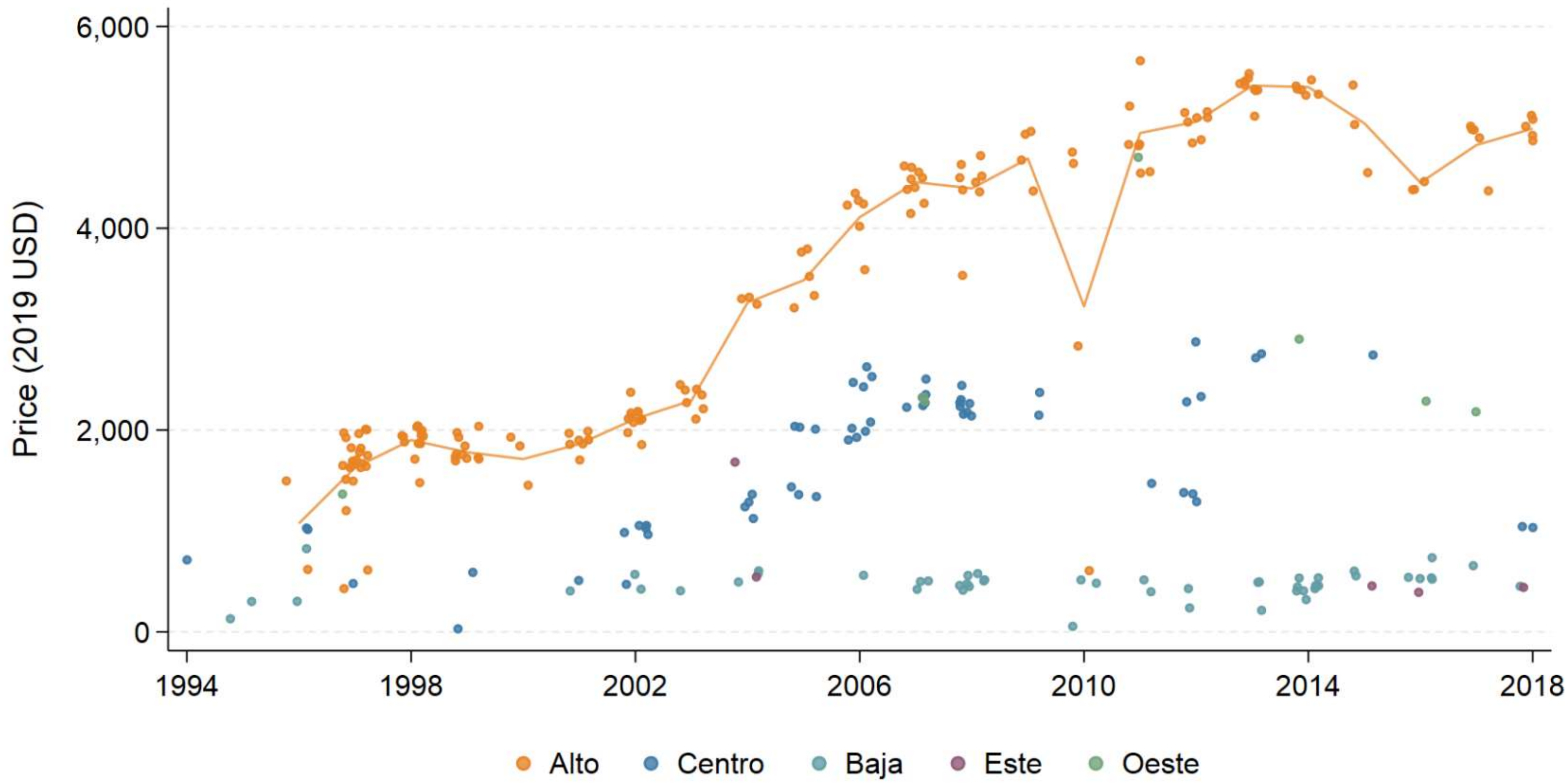
Mojave Water Market: Depth to Groundwater

Figure 1: Depth to groundwater before and after adjudication



Source: Ayres et al. (2021, JPE)

Mojave Water Market: Prices



Mojave Water Market

Figure B.1: Agricultural revenue before and after adjudication

- Agriculture declined, but benefits shared broadly
- Benefits of $400-500 million, in large part to farmers (Ayres et. al., 2021)
- Despite effectiveness of Mojave water market, initial stakeholder buy-in was difficult

Contact Information

If you have any questions about this presentation, please contact Michael H. Taylor at taylor@unr.edu or (775) 784-1679.

Acknowledgements

Nevada Division of Water Resources

Nevada Department of Conservation & Natural Resources

University of Nevada Cooperative Extension

Nevada Agricultural Experiment Station
SUSTAINABLE SCIENCE FOR LIFE

Do Environmental Markets Improve on Open Access? Evidence from California Groundwater Rights

Andrew B. Ayres

Public Policy Institute of California

Kyle C. Meng

University of California Santa Barbara and National Bureau of Economic Research

Andrew J. Plantinga

University of California Santa Barbara

Environmental markets are widely prescribed as an alternative to open access regimes for natural resources. We develop a model of dynamic groundwater extraction to demonstrate how a spatial regression discontinuity design that exploits a spatially incomplete market for groundwater rights recovers a lower bound on the market's net benefit. We apply this estimator to a major aquifer in water-scarce southern California and find that a groundwater market generated substantial net benefits,

We acknowledge helpful comments from Max Auffhammer, Spencer Banzhaf, Lint Barrage, Otavio Bartalotti, Youssef Benzarti, Chris Costello, Robert Heilmayr, Josh Hill, Matt Kahn, Bryan Leonard, Gary Libecap, Heather Royer, Randall Rucker, Doug Steigerwald, Walter Thurman, Gonzalo Vazquez-Bare, Randy Walsh, Paige Weber, and Jinhua Zhao as well as participants at the National Bureau of Economic Research Environmental and Energy Economics Summer Institute and at other seminars and conferences. We thank Chris Free, Tracey Mangin, Gokce Sencan, and Vincent Thivierge for assistance with data. This research was funded by a grant through the University of California Office of the President (MR-15-328650, Legal Economic Data and Analysis of Environmental Markets) and supported in part by the Property and Environment Research Center. Data are provided as supplementary material online. This paper was edited by Chad Syverson.

Electronically published July 21, 2021
[*Journal of Political Economy*, 2021, vol. 129, no. 10]

as capitalized in land values. Heterogeneity analyses point to gains arising in part from rights trading, enabling more efficient water use across sectors. Additional findings suggest that the market increased groundwater levels.

I. Introduction

For almost two centuries, scholars have recognized that common-pool resources, if left under open access conditions, tend to be used inefficiently (Lloyd 1833; Coman 1911; Gordon 1954; Hardin 1968; Ostrom 1990). This issue is even more relevant today, with increasing concern over the status of natural resources, such as fresh water, fisheries, and the global climate (Stavins 2011).

In many settings, this problem of the commons arises because a market for property rights to the resource is missing (Coase 1960). This insight underlies the modern framework for environmental markets—as suggested by Crocker (1966) and Dale (1968) and formalized by Montgomery (1972)—whereby a regulator sets a limit on total extraction, allocates extraction rights to users equaling this total, and oversees rights trading.[1] Today, some form of environmental market covers 30% of global fisheries (Costello et al. 2016), accounts for over $36 billion in global ecosystem service payments (Salzman et al. 2018), and governs over 10% of global greenhouse gas emissions (World Bank Group 2020).[2]

The effectiveness of environmental markets, however, is predicated on a number of theoretical assumptions. A large literature has explored how the presence of market power (Hahn 1984; Malueg 1990), inadequate enforcement (Malik 1990), transaction costs (Stavins 1995), and other barriers (see Cropper and Oates 1992) may adversely affect environmental market performance. Given how pervasive these features are in practice, it is an empirical question whether net benefits are generated when an environmental market replaces an open access regime and, if so, why.[3]

Researchers face three empirical challenges when quantifying the net benefit of an environmental market. First, one must track all agents that are directly affected by the regulated environmental good. This may be difficult for goods such as air quality, where the (possibly unobserved) set of beneficiaries is highly dispersed. Second, one needs a measure of

[1] This additional structure overcomes some practical impediments to Coase's original formulation. In particular, having a regulator set a total extraction limit and manage rights trading can avoid transaction costs that may limit Coasian bargaining.

[2] In fisheries, such policies are often called rights-based management or individual transferable quotas. For air pollution and greenhouse gas emissions, they are typically known as cap and trade.

[3] Recent surveys of implemented environmental markets can be found in Tietenberg (2003), Freeman and Kolstad (2006), Goulder (2013), and Schmalensee and Stavins (2017).

the good's economic value, which in the case of a stock resource, such as groundwater or fish, must reflect both current and future values. Third, environmental markets are often adopted when a resource is in a critical state of overextraction (Shertzer and Prager 2006; Costello et al. 2008; Worm et al. 2009; Mangin et al. 2018). As such, simple comparisons between resources governed by a market and under open access conditions may be confounded by differences in unobserved resource characteristics.

This paper studies a particular market for groundwater rights in southern California's Mojave Desert.[4] We select this setting for two reasons. First, groundwater is a critical and increasingly scarce natural resource. It provides 50% of potable and 40% of irrigation water globally (Giordano 2009; Aeschbach-Hertig and Gleeson 2012), yet one-third of the world's largest aquifers are facing declining water levels (Richey et al. 2015). Moreover, groundwater scarcity is expected to worsen under demographic trends and anthropogenic climate change (Vörösmarty et al. 2000; Covich 2009; McDonald et al. 2011; Elliott et al. 2014; Prudhomme et al. 2014; Ferguson et al. 2018). Second, our setting addresses the aforementioned empirical challenges. Land parcels within a known area of the Mojave Desert possess tradeable groundwater rights, the current and future values of which are capitalized in land values. Importantly, this market for groundwater rights does not cover the entire aquifer, allowing us to address endogeneity concerns by applying a spatial regression discontinuity (RD) design across the groundwater market boundary.

Our identification strategy leans heavily on renewable resource theory. The estimand of interest is the parcel-averaged difference in (potential) land prices between a groundwater market and an open access regime. As in any potential outcomes framework, this difference cannot be estimated because land prices are not observed under both regimes. However, when a groundwater market does not spatially cover the entire aquifer, an opportunity arises for comparing land prices of parcels subject to the groundwater market with those of parcels under open access, all within the same observed setting. We develop a model of dynamic groundwater extraction to demonstrate that our estimand is ambiguously signed when the market for groundwater rights is spatially incomplete. A spatial RD design comparing land prices on either side of the groundwater market boundary removes potential endogeneity concerns, as groundwater characteristics are likely continuous across the boundary. However, that same identifying assumption also removes changes in the water table, a potentially important consequence of the groundwater market, such that an RD estimate deviates from the estimand. We turn to our model to sign this bias, showing that the RD estimate yields a weak lower bound on the local

[4] Interest in California water use in economics dates back to at least Coman (1911) in the inaugural issue of *American Economic Review*, revisited recently by Libecap (2011).

average net benefit of a spatially incomplete groundwater market as well as for the population average net benefit under further assumptions.

Our empirical setting is the Mojave Desert, the driest desert in North America and yet a region that produces water-intensive crops. Mojave's verdant, irrigated farms in the midst of a barren desert have long been a poster child for inefficient water use. This stark contrast arises because underneath the Mojave Desert lies one of California's largest aquifers, which has historically been extracted for agricultural use under open access conditions. Agricultural irrigation led to severe groundwater depletion: between 1964 and 1990, the water table fell by 30 feet. Following failed attempts to limit pumping by creating a groundwater market in the 1960s and 1970s, a court process beginning in 1990 and finalized in 1996 created a system known as adjudication that imposes a total limit on groundwater pumping and allocates tradeable pumping rights to users within a particular spatial area. Importantly, this area—jointly determined by the boundaries of a preexisting regulatory institution and a surface topographical feature—did not include all land parcels overlying the aquifer. This distinct spatial feature, together with a requirement that reported land values for agricultural parcels include the value of groundwater access, enables our RD estimator.[5]

We estimate that agricultural land values on the groundwater market side of the boundary are, on average, 220% higher than on the open access side. To validate the magnitude of this estimate, we show that it is less than an upper bound on the policy's net benefit: the total value of groundwater rights attached to adjudicated land parcels. We confirm that relevant covariates do not exhibit discontinuities at the boundary. We also demonstrate that our RD estimate is robust to alternative statistical modeling assumptions, bandwidth choices, potential error in land value assessments, how the boundary is defined, and other empirical concerns. Reassuringly, we do not detect RD effects using placebo boundaries falsely set within the groundwater market and open access areas. Using earlier land value data, we also fail to detect statistically significant RD estimates prior to the 1990s. In particular, the point estimate using 1976–79 land values is 37% of the estimate using post-1996 values. Given earlier failed attempts at establishing a similar groundwater market, a nonzero effect prior to the 1990s may reflect anticipation of an eventual groundwater market.

One potential explanation for our large RD estimate is that groundwater trading provides agricultural landowners the opportunity to capitalize

[5] Groundwater rights have also been introduced elsewhere in California, and in total 26 basins have well-defined rights. Twenty of those basins have rights defined volumetrically, and trading is allowed in 19 of those. These 19 systems represent 4% of California's aquifers. However, the spatially incomplete nature of the Mojave groundwater market, combined with rights trading, is unique in California.

on water's market value. For the Mojave aquifer, higher water values likely come from municipalities, particularly in the southern, more urban areas overlying the aquifer. Indeed, heterogeneity analysis reveals a substantially higher RD estimate in the southern part of the aquifer compared with the north. This suggests that the ability to trade groundwater rights enhances land values by reallocating water away from water-intensive agriculture and toward meeting growing urban demand.[6] Accounting for these heterogeneous effects and further assuming that unobserved characteristics are uncorrelated with distance to the boundary, we calculate that the groundwater market produced an aggregate net benefit of $350 million (in 2015 dollars) for agricultural parcels, or a 40% increase in aggregate land value.

Our RD approach has two primary drawbacks. First, by measuring effects at the groundwater market boundary, our estimate does not capture potential benefits from higher groundwater levels under adjudication relative to the open access counterfactual. Instead, we turn to three additional pieces of evidence, all of which point toward increased groundwater levels: (1) we detect a positive trend break in average groundwater levels when the adjudication's pumping restrictions began for most users; (2) we detect an RD jump in groundwater well drilling for open access parcels beginning at that same moment, consistent with increased groundwater under adjudication that spills over into open access areas; and (3) we document that prices for groundwater rights have been consistently positive, which our theory shows is a sufficient condition for increased groundwater levels under adjudication relative to open access. The second limitation of our RD approach is that we cannot apply it to urban areas because they obtain water from municipal water systems, not local groundwater pumping. We extend our theory to show how data on aggregate urban water allocation and consumption combine to produce a back-of-the-envelope aggregate net benefit of $72–$131 million (in 2015 dollars) for urban areas. Altogether, the aggregate net benefit to agricultural and urban areas of the groundwater market is $422–$481 million. In contrast, the initial setup cost of the groundwater market during the 1990s was $40 million (in 2015 dollars; Figueroa 2001).

This paper contributes to a recent literature using quasi-experimental techniques to understand the consequences of environmental markets. Studies of air pollution and greenhouse gas markets typically examine only regulatory costs (Petrick and Wagner 2014; Calel and Dechezleprêtre 2016; Meng 2017; Calel 2020) or benefits (Fowlie et al. 2012; Deschenes, Greenstone, and Shapiro 2017; Hernandez-Cortes and Meng

[6] While our RD design prohibits us from exactly isolating the gains from groundwater trading, a back-of-the-envelope calculation suggests that at most 39% of the net benefit can be attributed to trading.

2021), rarely both. A larger literature exists for fisheries, reflecting the many instances of market-based management in that domain. These papers have found that rights-based management tends to reduce effort (Hsueh 2017; Costello and Grainger 2018; Isaksen and Richter 2018), distribute effort more evenly across time (Birkenbach et al. 2017), and increase resource levels (Costello et al. 2008), efficiency (Grafton et al. 2011), and revenues (Scheld et al. 2012).[7] For groundwater in particular, Drysdale and Hendricks (2018) and McLaughlin (2020) find reduced water use and higher groundwater levels, respectively, following the introduction of a water market. These outcomes, however, do not fully capture current and future net benefits of an environmental market. In our setting, the value of groundwater access is bundled together with the value of a land parcel. As such, we are able to follow the Ricardian tradition by studying land prices that capture the current and future net benefit of a groundwater market.

Another related literature in development economics and economic history employs quasi-experimental approaches to study the consequences of stronger property rights for land through, for example, more secure land title (Besley 1995; Besley and Burgess 2000; Banerjee et al. 2002; Field 2007; Galiani and Schargrodsky 2010), lower enforcement costs (Hornbeck 2010; Libecap and Lueck 2011), and enhanced access rights (Iwanowsky 2019). In these settings, land—the resource of interest—was privatized to a certain degree prior to treatment. A test of the consequences of introducing property rights requires a resource that was initially held in common. Our setting satisfies this requirement.[8]

Finally, our study informs the increasing need for groundwater management, particularly under anthropogenic climate change. For California, groundwater pumping—which historically provides one-half of the state's fresh water—has long been unsustainably extracted, with recent consequences especially acute during a prolonged drought (California Department of Water Resources 2015). In response, California passed the Sustainable Groundwater Management Act, an unprecedented law requiring users of overextracted aquifers to adopt stringent management plans. Groundwater markets are considered a key policy instrument under the act (Aladjem and Sunding 2015; Babbitt et al. 2017; Green Nylen et al. 2017; Bruno and Jessoe 2021).[9]

The paper is structured as follows. Section II provides background on the Mojave aquifer and its spatially incomplete market for groundwater rights. Section III introduces a dynamic model of groundwater extraction

[7] In another quasi-experimental study, Kroetz et al. (2015) examine how fishing permit prices diverge following the imposition of trading restrictions.

[8] Note that in our setting landowners have rights to land, but groundwater use is still initially under open access.

[9] Surface water trading has also received renewed interest. Hagerty (2019) demonstrates potentially large gains from surface water trading in California. Rafey (2020) quantifies the gains from trade from observed surface water trading in southeastern Australia.

under open access and incomplete groundwater market regimes, which informs our empirical strategy in Section IV. Section V details data sources. Section VI presents our main RD results, robustness checks, and heterogeneity analyses. Section VII quantifies the aggregate net benefit for agricultural and urban areas and presents further evidence that the market has increased groundwater levels. Section VIII concludes.

II. Background

The Mojave Desert, located northeast of Los Angeles in southern California's San Bernardino County, is the driest desert in North America, receiving on average less than 2 inches of rainfall annually. Yet farmers in the Mojave Desert have historically produced alfalfa, pistachios, and stone fruits, all highly water-intensive crops. This production is possible in part because beneath this desert lies one of California's 10 largest groundwater resources, which has historically been extracted for agricultural use under open access conditions.[10]

In recent decades, open access pumping has led to a dramatic drop in the aquifer's water table. Figure 1 plots the average depth from surface to the water table across monitoring wells in the Mojave Desert: between 1964 and 1990, the water table fell by 30 feet. From 1966 to 1976, there was an initial but failed attempt on the part of the regional water regulator, the Mojave Water Agency, to allocate water rights through a system known as adjudication. Discussions about adjudication continued throughout the 1970s and 1980s, culminating in a new adjudication lawsuit in 1990. In 1993, an agreement comprising 75% of groundwater users was reached. In 1996, the local court sanctioned an agreement that applied to nearly all users.

Adjudication has two components. First, water users received individual, perpetual annual groundwater pumping rights, defined as their proportion of average annual pumping during the 1986–90 base period. To stabilize groundwater levels, the aggregate annual allowable pumping across the aquifer ramps down over time. Each year, a perpetual right holder is able to pump an amount equal to their right, scaled back proportionally by the degree of aggregate ramp down. Second, users can buy or sell paper

[10] Ostrom (2008, 11) defines an open access resource as "a common-pool resource that anybody can enter and/or harvest." This definition is a reasonable approximation of the Mojave aquifer prior to adjudication. For overlying agricultural users, California law requires groundwater use to be reasonable and beneficial. In practice, this criteria has historically allowed de facto open access, as there has been unrestricted groundwater pumping for agricultural use in arid regions. Those without overlying land parcels, including municipalities but potentially any other user as well, were also able to access the aquifer, with the caveat that their rights had lower priority than those of overlying users. While not exactly matching a textbook definition of pure open access, we think open access remains the best description of the overall regime governing groundwater use prior to adjudication.

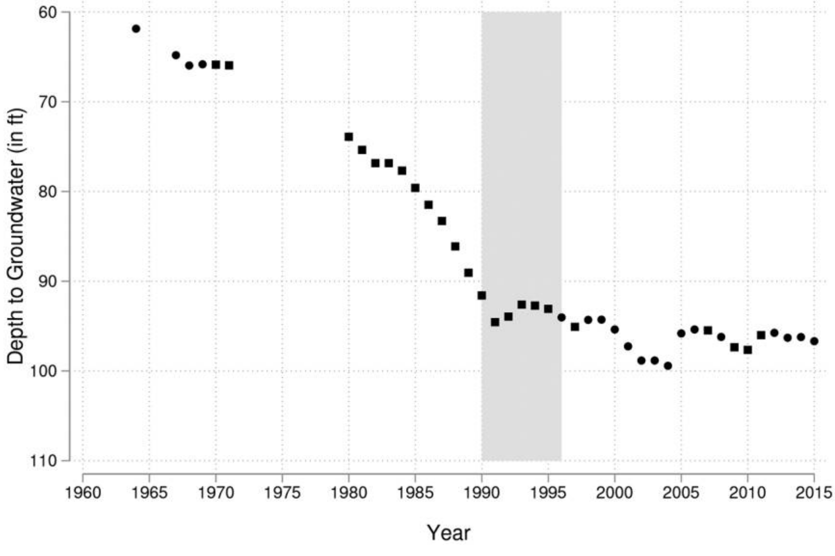


Fig. 1.—Depth to groundwater before and after adjudication. Vertical axis shows average distance (in feet) to water table across monitoring wells in the Mojave Desert. Horizontal axis indicates years. Circles indicate years for which data exist for all monitoring wells. Squares indicate years for which values from one or more monitoring wells are linearly interpolated. Shaded area marks the period from 1990 (when the initial adjudication lawsuit was filed) to 1996 (when the final adjudication court ruling was issued). Source: USGS.

groundwater rights through either annual leases or transfers of perpetual rights. These are paper rights in the sense that users do not transfer physical water. Instead, they exchange pumping rights with any other user (i.e., agricultural landowner or municipality), who also overlies the groundwater resource. Transfer of rights to users not overlying the resource would require physically transporting pumped water outside the basin and is prohibited. The resulting water market enables users to reap any allocative efficiency gains arising from the sale of rights to other users. This is an important change from the prior open access regime, in which users do not own rights to the water and thus can pump water only for own use.[11]

Adjudication also brought an added benefit to urban areas, where residents access groundwater through municipal water systems and not via their own pumping. Whereas agricultural landowners extracted under unrestricted open access prior to adjudication and thus were presumably at a private optimum, municipalities were previously restricted because

[11] In other settings, there may be a less formal arrangement involving local management of groundwater resources by a limited group of users, typically referred to as groundwater management districts (Edwards 2016). Local resource management is common in fisheries, referred to as territorial user rights fisheries, and the subject of a large theoretical and empirical literature (Janmaat 2005; Sampson and Sanchirico 2019).

they had lower priority access, entitling them to extract groundwater only beyond what was needed to satisfy agricultural demands. By redefining groundwater rights and introducing the ability to trade, adjudication elevated the rights of municipalities—and, by extension, urban residents—to be on par with agricultural rights, thus lifting restrictions and allowing for expanded pumping.

Despite these advantages, several features of the Mojave adjudication system deviate from a textbook optimal policy. First, it is unclear whether simply stabilizing the water level at its preadjudication level corresponds to an optimal water table height. Second, in addition to the prohibition on physical water transfers out of the basin, limits are also placed on water right trading across space and time. Landowners can trade groundwater rights only with overlying landowners or municipalities within the same subarea of the groundwater resource. Depending on how much these subareas are hydraulically connected, inefficiencies may arise from having separate groundwater markets. Likewise, water rights can be banked only 1 year ahead and cannot be borrowed from the future, which limits intertemporal smoothing of water consumption.

The most notable feature of the Mojave adjudication that deviates from an ideal groundwater market is that rights were not assigned over the entire spatial extent of the groundwater resource. Figure 2 illustrates the spatial boundary of the adjudication system (dark gray and light gray lines) and the subsurface extent of the entire hydraulically connected Mojave groundwater system (gray shading), which we henceforth refer to simply as the Mojave aquifer.[12] Observe that the spatial footprint of the adjudication system and Mojave aquifer areas do not perfectly overlap, so that some areas overlying the aquifer fall under adjudication (i.e., gray areas within dark gray and light gray lines) while others remain under open access (i.e., gray areas outside dark gray and light gray lines).

It is important to clarify how the adjudication boundary was drawn. Specifically, it is the spatial intersection of two regions: the jurisdictional area of the preexisting Mojave Water Agency (shown by light gray line segments) and the physical surface drainage area of the Mojave River (shown by dark gray line segments). The straight-line boundaries of the Mojave Water Agency, formed in 1960 with largely unchanged boundaries since then, are based on the regular grid lines imposed by the Public Land Survey System from the eighteenth century and thus likely unrelated to subsurface groundwater

[12] The key to defining the spatial extent of the relevant groundwater resource is hydraulic connectivity such that extraction in one location can affect the water table in other locations. The gray area in fig. 2 shows the hydraulically connected groundwater resources in the study area, as confirmed by hydrologists at the Mojave Water Agency. State and federal agencies may define multiple administrative basins in the region that need not be hydraulically independent. For example, the gray area in fig. 2 consists of several basins defined by California's Department of Water Resources that are largely hydraulically connected.

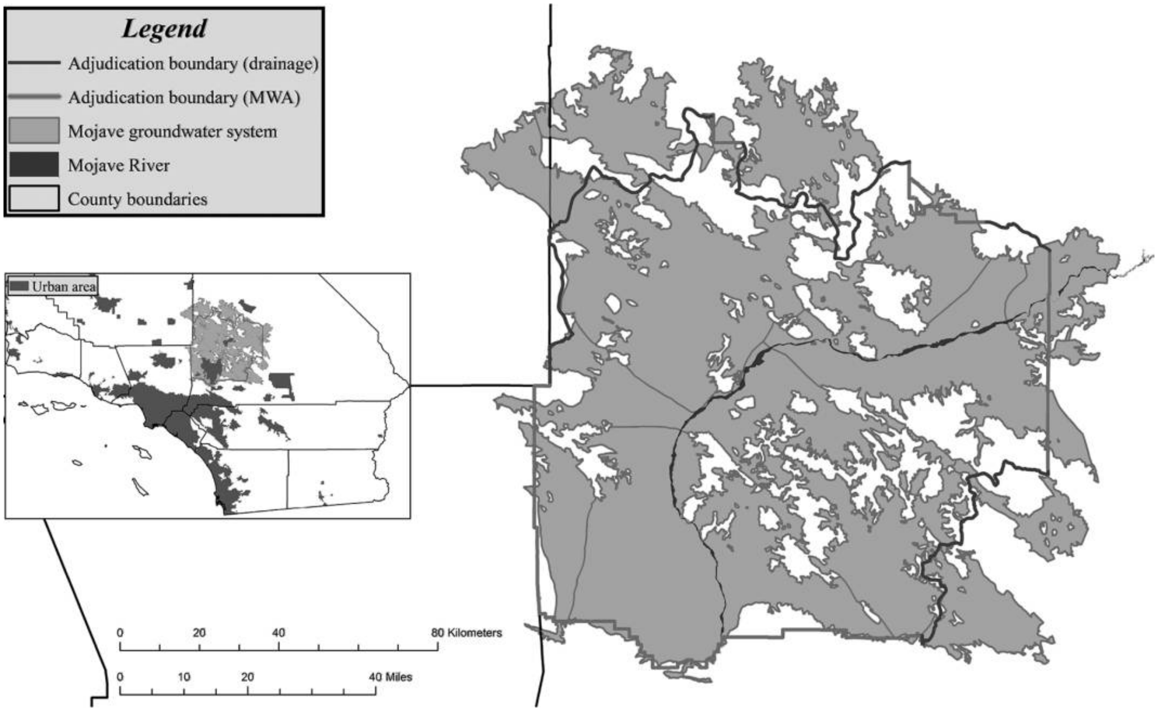


Fig. 2.—Groundwater market and aquifer in Mojave Desert. Gray shaded area shows the spatial extent of the hydraulically connected Mojave groundwater system. Dark gray (light gray) line segments track the groundwater market area, as defined by the spatial extent of the Mojave River drainage basin (Mojave Water Agency). Inset map shows the Mojave aquifer relative to urban areas, as defined by the Federal Highway Administration, in the broader southern California region. A color version of this figure is available online.

characteristics. Likewise, the drainage extent of the Mojave River, which is determined by surface topographical features, is also plausibly exogenous to groundwater characteristics.[13]

A spatially incomplete groundwater market, coupled with knowledge of how its boundary was drawn, provides an opportunity to apply a spatial RD design. Before we do so, it is instructive to explore what existing data indicate regarding the net benefit of the Mojave adjudication system. Figure 1 shows that groundwater levels indeed began to stabilize in the 1990s. However, stabilized water levels alone do not imply positive net benefits for landowners under adjudication since pumping restrictions may be costly and transaction costs large. Furthermore, as our theory will show, stabilized water levels are also consistent with continued open access conditions that had yet to reach a steady state prior to adjudication. Trends in agricultural activity are also inconclusive. Figure B.1 (figs. B.1–B.7 are available online) shows that agricultural revenue in the Mojave Desert declined after adjudication was finalized. However, agricultural revenue does not capture possible gains from the reallocation of water to other sectors (e.g., urban water use) and thus does not provide a clear indication that adjudication benefited landowners.

Alternatively, one can follow the Ricardian tradition and examine land prices. This is possible in our data setting because the value of groundwater access in San Bernardino County is bundled together with the value of a land parcel. As such, land prices reflect the present discounted value of rental streams from both land and water assets.[14] For open access parcels, land prices capture the value of unrestricted groundwater pumping for own use. For parcels under adjudication, land prices reflect the cost of restricted groundwater pumping as well as the benefits of a higher groundwater level and the potential gains from trading pumping rights. We now turn to a theoretical model of dynamic groundwater extraction to formalize what drives these land prices and how they relate to our empirical strategy.

III. Theory

This section develops a model of dynamic groundwater extraction for the Mojave aquifer. Recognizing that the Mojave adjudication regime deviates in practice along several dimensions from an optimal policy, we explicitly avoid characterizing optimality and instead consider a model that closely mirrors the policy's objective to stabilize water levels using spatially

[13] As robustness checks, we test whether potentially relevant surface topographical features vary smoothly across the boundary. We also examine whether parcels near these two boundary definitions exhibit different RD estimates.

[14] Land prices, however, do not capture the one-time sunk costs of setting up the adjudication system.

incomplete groundwater rights.[15] In particular, to replicate observed falling groundwater water levels prior to adjudication, as shown in figure 1, we begin with all land parcels over the aquifer extracting groundwater under open access but without having yet reached a steady state. We then model land price dynamics under counterfactual and factual regimes for the period after adjudication is introduced. In the first (counterfactual) regime, we model land price dynamics if open access conditions had continued for all parcels over the aquifer. In the second (factual) regime, we model land price dynamics following the introduction of adjudication's system of spatially incomplete tradeable groundwater rights.[16]

Our theory generates several predictions that are used for interpreting our spatial RD estimator, presented in section IV. First, we show that the difference in land prices between the two regimes, our estimand of interest, is of ambiguous sign. Intuitively, this is because relative to open access, adjudication imposes the cost of restricted pumping but also generates benefits from a higher water table and the ability to trade groundwater rights. Next, we demonstrate that a spatial RD estimator comparing parcels under adjudication and open access at the adjudication boundary produces a lower bound for the estimand at the boundary. This is because a spatial RD estimator, by design, omits differences in water table height, thus excluding the benefit of a higher water table due to adjudication. Finally, because water table levels are lower at the boundary than in the interior of the adjudication area, the RD estimator is also a lower bound on the estimand in the interior.

Throughout this section, we focus on agricultural parcels for which groundwater is appurtenant, or tied, to the overlying land surface. This implies that water access is determined by local groundwater levels, which facilities our spatial RD design in section IV. In contrast, urban areas receive piped water from municipal water systems whose groundwater access is determined regionally and thus cannot be examined with a spatial RD approach. We return to a discussion of net benefits for urban areas in section VII.A.

A. *Setup*

There are N identical agricultural landowners, each of whom has a land parcel that overlies $1/N$ of the area of the aquifer. Instantaneous profits

[15] An optimal policy will always do at least as well as open access. To be useful for empirical testing, our model must leave open the question of whether spatially incomplete tradeable groundwater rights yield net benefits.

[16] A comparison of land prices under the two regimes is valid only if the initial groundwater level is the same in both cases, implying that our theory must necessarily be dynamic in order to characterize adjustments to the steady states under open access and incomplete tradeable rights.

are given by $\pi(w, h)$ where w is the pumping rate and h is the water table height, measured as the vertical distance from the bottom of the aquifer to the water level. $\pi(w, h)$ is assumed to be concave and singled peaked in w, increasing in h, and $\pi_{wh} > 0$ since raising the water table height reduces the cost of pumping, making the marginal unit of water more profitable. The initial height of the water table is h_0, and the instantaneous rate of change in the water table height is $\dot{h}(t)$, where t is time. After the initial period, dynamics of h differ depending on whether the aquifer is under full open access or incomplete tradeable groundwater rights, as we discuss below.

B. *Full Open Access*

Under full open access, profit-maximizing landowners ignore any effects of their pumping on the water table, solving at each instant in time:[17]

$$\max_{w} \pi(w, h). \tag{1}$$

The first-order condition $\partial\pi/\partial w = 0$ defines $w^a(h)$, the pumping rate as a function of the height of the water table (a indicates full open access). Using Cramer's rule, $dw^a/dh = -(\pi_{wh}/\pi_{ww}) > 0$, by the concavity of the profit identity, $\pi_{ww} < 0$, and $\pi_{wh} > 0$. Pumping rates under open access increase with the height of the water table.

1. Transition and Steady State

Under open access, all users pump at the same rate, and so the water table height is the same for all landowners. It evolves according to

$$\dot{h}^a(t) = R - Nw^a(h(t)), \tag{2}$$

where R is natural recharge and $Nw^a(h(t))$ is aggregate pumping.[18] Consistent with figure 1, we assume that the aquifer is out of steady state initially and that aggregate pumping $Nw^a(h_0)$ exceeds recharge. By equation (2), this results in a declining water table. However, the drop in the water table height causes the open access pumping rate to fall by Cramer's rule. A steady state is reached when pumping is equal to recharge.[19] The steady

[17] Our open access model is a limiting case of uncoordinated spatial ownership (Kaffine and Costello 2011), where each user has exclusive access to the water beneath their property, but pumping by other landowners gives rise to a stock externality.

[18] The volume of the aquifer is normalized to 1 so that volumetric variables R and w are conformable with h.

[19] To ensure that the steady state occurs at a strictly positive value of h, we assume $w^a(0) < R/N$. This assumption is justified for the Mojave aquifer, given evidence of extremely deep aquifers in the region that go far beyond the depth of existing wells (Kang and Jackson 2016; Perrone and Jasechko 2019).

state is defined as $\bar{h}^a$ such that $\dot{h}^a = R - N\bar{w}^a = 0$, where $\bar{w}^a = w^a(\bar{h}^a) = R/N$.

The dynamics of the full open access system are illustrated in figure 3*A*. For a given value of h, the pumping rate is $w^a(h)$. Thus, any $w \neq w^a(h)$ moves immediately to the $\dot{w} = 0$ locus defined by $w^a(h)$. From there, the dynamics of the system are governed by equation (2). The gray line in figure 3*A* shows the transition to the steady state from the initial height of $h_0 > \bar{h}^a$. When $h < \bar{h}^a$, the pumping rate and the water table height increase until the steady state is reached. In summary, under the full open access regime, we have $h_0 \geq h^a(t) \geq \bar{h}^a$ and $w^a(h_0) \geq w^a(h^a(t)) \geq \bar{w}^a$ for $t \geq 0$.

2. Land Price

Under perfect competition, the price of a land parcel is equal to the present discounted value of the infinite stream of profits. Thus, the full open access land price is given by

$$V^a = \int_0^\infty \pi(w^a(s), h^a(s))e^{-\delta s} ds, \tag{3}$$

where δ is the discount rate and the time interval covers both the transition period and the steady state.

C. *Spatially Incomplete Groundwater Rights*

Property rights are introduced to stabilize the water table at h_0, preventing the draw down of the aquifer that occurs under open access. If all N landowners were under the property rights regime, the regulator would simply assign individual pumping rights equal to R/N. If users pump their full allocation, then by equation (2), the water table remains at its initial level h_0. In the steady state, the same volume of water is pumped as under the open access regime, but because $h_0 > \bar{h}^a$, profits are higher than under open access (Gisser and Sanchez 1980). The steady state is more complicated when property rights are incompletely assigned over the aquifer because users can pump at different rates.[20]

We examine this setting by modeling the two components of the Mojave adjudication regime: a restriction on pumping to stabilize water levels and tradeable property rights to pump groundwater. First, we characterize how pumping restrictions allow for stabilization of the water table. We then show how the market value of tradeable pumping rights is capitalized into land prices.

[20] See Costello et al. (2015) for a comparison of open access, incomplete property rights, and complete property rights regimes.

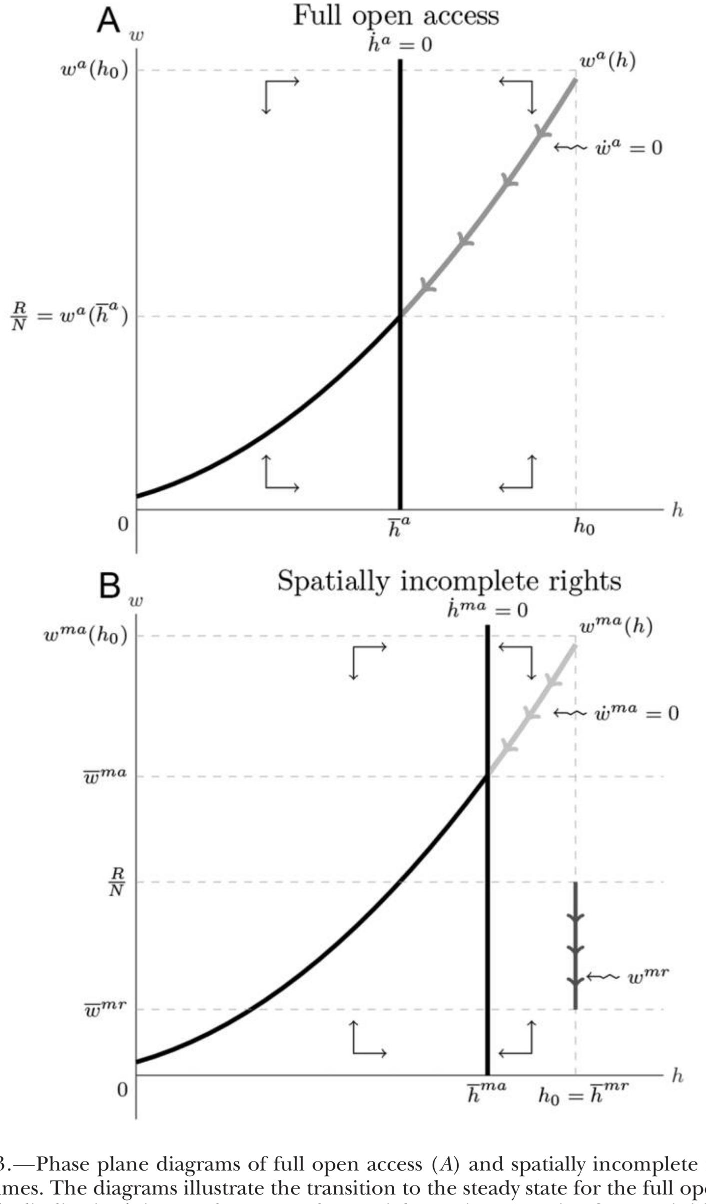


FIG. 3.—Phase plane diagrams of full open access (*A*) and spatially incomplete rights (*B*) regimes. The diagrams illustrate the transition to the steady state for the full open access and adjudication's incomplete groundwater rights regimes, starting from an initial water table height h_0. The directionals in each isosector apply to the open access users and are described in the text. *A*, The gray line is the transition path to the steady state at $\bar{h}^a$ and $w^a(\bar{h}^a)$ for open access users under the full open access regime. *B*, Under the adjudication regime, a representative open access parcel follows the light gray line to the steady state at $h = \bar{h}^{ma}$ and $w = \bar{w}^{ma}$. A representative parcel with groundwater rights follows the dark gray line with a constant stabilization target of $\bar{h}^{mr}$ and an exogenous pumping rate (determined by the regulator) that reaches a steady state at $w = \bar{w}^{mr}$. A color version of this figure is available online.

Under incomplete rights, only a share of the N landowners hold property rights, with the rest of the landowners remaining under open access. Define $\alpha \in [0, 1]$ as the share of open access landowners. We assume that all landowners under the property rights regime (indicated by mr, where m denotes the incomplete [or mixed] regime and r indicates users with rights) hold rights to an endowment of water w^e, whereas open access users (indicated by ma) are unconstrained. Open access users continue to solve the profit maximization problem in 1; however, rights holders now solve

$$\max_w \pi(w, h) \text{ subject to } w \leq w^e. \tag{4}$$

Assuming $w > 0$, the solution to equation (4) satisfies the first-order condition $\partial\pi/\partial w = \lambda^{mr}$, where λ^{mr} is the shadow value on the constraint. The complementary slackness condition is $\lambda^{mr}(w - w^e) = 0$, which says that at the optimum, either the constraint binds or the shadow value of water equals zero (or both). The solution to equation (4) is denoted w^{mr} and defined as the posttrading volume of water pumped by landowners in the adjudication area and applied to their land. For now, we assume that the endowments w^e are the same for all landowners in the adjudication area, which implies no trading among agricultural users.[21] We will relax this assumption below. Given the intent to prevent further groundwater drawdown under open access, the constraint in equation (4) binds, and thus $w^{mr} = w^e$ for all rights holders.

To simplify the analysis, we focus on two representative users, one within the adjudication area with water table h^{mr} and the other in the open access area with water table h^{ma}. The dynamics of the water table are described by a variant of equation (2):[22]

$$\dot{h}^{ma} = \alpha R + \theta(h^{mr} - h^{ma}) - \alpha N w^a(h^{ma}), \tag{5}$$

$$\dot{h}^{mr} = (1 - \alpha)R + \theta(h^{ma} - h^{mr}) - (1 - \alpha)N w^{mr}, \tag{6}$$

where it is assumed that recharge occurs uniformly throughout the aquifer.[23] Because of gravity, differences in the water table height produce a flow of water, dictated by $\theta \in [0, 1]$, from one area to another.

[21] Because landowners are identical in all respects, shadow values are equal at the initial endowment and there are no gains from trade.

[22] We suppress time arguments except when it is necessary to clarify a variable's dependence on time.

[23] The assumption of uniform recharge can be relaxed without changing the key insights from our theory.

1. Stabilization and Transition

We assume that the goal of property rights is to stabilize the aquifer within the adjudication area at $\bar{h}^{mr} = h_0$ by imposing the pumping limit $w^{mr}(t)$. That is, the pumping limit is set in each period to achieve

$$\dot{h}^{mr} = (1-\alpha)R + \theta(h^{ma}(t) - \bar{h}^{mr}) - (1-\alpha)Nw^{mr}(t) = 0. \quad (7)$$

Although the water table is stabilized in the adjudication area, it continues to be drawn down in the open access area. Consider $\dot{h}^{ma}$ at $t = 0$:

$$\dot{h}^{ma} = \alpha R + \theta(\bar{h}^{mr} - h^{ma}) - \alpha N w^a(h^{ma}) = \alpha R - \alpha N w^a(h_0), \quad (8)$$

where $\bar{h}^{mr} = h^{ma} = h_0$. As under full open access, open access users under incomplete rights pump more than recharge at h_0 and $\dot{h}^{ma} < 0$. The pumping rate by open access users depends only on the water table height according to $w^{ma} = w^a(h^{ma})$, as in the full open access case. The dynamics of the incomplete rights system is illustrated in figure 3*B*, where the light gray line depicts the transition to the steady state for open access users.[24] Although the same trajectory is followed as under full open access, there is a positive flow of water to the open access area ($\bar{h}^{mr} - h^{ma} > 0$ for $t > 0$), which slows the decline in h^{ma} relative to the full open access case (we prove this result in sec. III.D).

In order to keep $\bar{h}^{mr}$ at h_0, $w^{mr}(t)$ must fall over time by equation (7). Solving for $w^{mr}(t)$ in equation (7) and taking the time derivative yields $\dot{w}^{mr} = \{\theta/[(1-\alpha)N]\}\dot{h}^{ma} < 0$. The transition path for the pumping rate in the adjudication area is depicted by the dark gray line in figure 3*B*. At $t = 0$, $w^{mr} = R/N$, which is established from equation (7) and the fact that $\bar{h}^{mr} = h^{ma}$ at $t = 0$. The pumping limit $w^{mr}(t)$ declines until steady states are reached in both areas, which we solve for next.

2. Steady States

Setting $\dot{h}^{ma} = 0$ in equation (5) and substituting $\bar{h}^{mr}$, we define the following relationship between steady-state water table heights:

$$\bar{h}^{mr} = \bar{h}^{ma} + \frac{\alpha}{\theta}(Nw^a(\bar{h}^{ma}) - R). \quad (9)$$

The assumption in footnote 24 implies that for any stabilization target for the adjudication area $\bar{h}^{mr}$, there is a unique steady-state water table $\bar{h}^{ma}$ and pumping rate $\bar{w}^{ma} = w^a(\bar{h}^{ma})$ in the open access area. We denote this mapping $q: \bar{h}^{mr} \rightarrow \bar{h}^{ma}$.

[24] An additional assumption is needed to guarantee that a unique value of h^{ma} solves $\dot{h}^{ma} = \alpha R + \theta(\bar{h}^{mr} - h^{ma}) - \alpha N w^a(h^{ma}) = 0$, as shown in fig. 3*B*: $d^2 w^a(h)/dh^2 \geq 0$, which holds if $\pi_{www}\pi_{wh} - \pi_{whh}\pi_{ww} \geq 0$.

The steady state for the adjudication area is found by substituting $\bar{h}^{mr}$ in equation (9) into equation (6) and setting $\dot{h}^{mr} = 0$, yielding

$$R - \alpha N w^a(\bar{h}^{ma}) - (1-\alpha)N\bar{w}^{mr} = 0, \tag{10}$$

Substituting $\bar{h}^{ma} = q(\bar{h}^{mr})$ and rearranging equation (10), we obtain

$$\bar{w}^{mr}(\bar{h}^{mr}) = \frac{R - \alpha N w^a(q(\bar{h}^{mr}))}{(1-\alpha)N}. \tag{11}$$

For a given stabilization target $\bar{h}^{mr}$, equation (11) gives the steady-state pumping limit $\bar{w}^{mr} = \bar{w}^{mr}(\bar{h}^{mr})$ that needs to be imposed on landowners within the adjudication area. The steady states are depicted in figure 3*B*.[25] In summary, under the incomplete property rights regime, we have $h_0 \geq h^{ma}(t)$, $w^a(h_0) \geq w^a(h^{ma}(t))$, and $w^{mr}(0) \geq w^{mr}(t)$ for $t \geq 0$.

3. Water Trading and Land Prices

Tradeable property rights allow right holders to exchange water with other agricultural landowners or with municipalities. If there are heterogeneous endowments, incentives for trading are created.[26] In particular, at the initial endowments, differences among landowners in the shadow values of water λ^{mr} imply gains from trade. If p^w is the unit price of water supported by a competitive water market, then landowners for whom $\lambda^{mr} < p^w$ ($\lambda^{mr} \geq p^w$) will be sellers (buyers) of water. When gains from trade are exhausted, $\lambda^{mr} = p^w$ for all landowners, and all landowners use the same amount of water w^{mr}. Thus, a landowner with a given endowment w^e makes net purchases from other agricultural landowners and municipalities equal to $w^{mr} - w^e$.[27]

Under incomplete property rights, the land price for a given owner in the adjudication area is

$$V^{mr} = \int_0^{\infty} [\pi(w^{mr}(s), \bar{h}^{mr}) - p^w(s)(w^{mr}(s) - w^e(s))]e^{-\delta s}ds. \tag{12}$$

Equation (12) captures temporary annual leases as well as transfers of perpetual groundwater rights. If a landowner sells her perpetual water rights to a municipality at a future time t, $w^{mr}(s) = 0$ for $s \geq t$ and the

[25] It can be shown that $\bar{w}^{ma} \geq \bar{w}^a \geq \bar{w}^{mr}$ and $\bar{h}^{mr} \geq \bar{h}^{ma} \geq \bar{h}^a$.

[26] In practice, other sources of heterogeneity, such as differences in production technologies or depths to groundwater, can also generate trading if endowments are homogeneous.

[27] Landowners under the Mojave adjudication are allowed to buy and sell pumping rights (i.e., paper trades) but not physical amounts of water. If we assume no banking or borrowing, which approximates the Mojave institution, the amount of water bought or sold by a landowner in each period, $w^{mr} - w^e$, must equal the amount applied to their parcel w^{mr} net of their endowment w^e.

proceeds from the sale, $\int_t^\infty p^w(s)w^e(s)e^{-\delta(s-t)}\,ds$, are capitalized into the current land price. The land price for landowners in the open access area is

$$V^{ma} = \int_0^\infty \pi(w^{ma}(s), h^{ma}(s))e^{-\delta s}ds. \tag{13}$$

We made the simplifying assumption above that there are single water table heights in the two areas. In reality, there is a declining gradient in the water table as one moves from the adjudication to the open access area. At the boundary of the two areas, the water table height is the same for parcels under the adjudication and open access areas. That is, denoting water table height at the boundary as $h^b(t)$, $\bar{h}^{mr} \geq h^b(t) \geq h^{ma}(t)$ for $t \geq 0$. This property has important implications for our RD estimator, as discussed in section IV.B.

D. *Comparing across Regimes*

We now compare land values between the full open access and incomplete property rights regimes to facilitate interpretation of an RD estimate in section IV.

PROPOSITION 1. If (i) $\bar{h}^{mr} \geq h^a(t)$, (ii) $\bar{h}^{mr} \geq h^{ma}(t)$, (iii) $h^{ma}(t) \geq h^a(t)$, and (iv) $w^a(h_0) \geq w^{ma}(t) \geq w^a(t) \geq w^{mr}(t)$ for $t \geq 0$, then

a. $V^{mr} - V^a \gtreqless 0$ (treatment effect has ambiguous sign);
b. $V^{mr} - V^{ma} \gtreqless 0$ (estimated effect has ambiguous sign);
c. $(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b)) \geq 0$ (estimated effect at the boundary is a lower bound for treatment effect at the boundary);
d. $(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) \geq 0$ (treatment effect at the boundary is a lower bound for treatment effect in the interior); and
e. $(d/dt)(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$ (the change over time in the estimated effect at the boundary has ambiguous sign).

Proof. We establish conditions i–iv here and prove proposition 1 in appendix sections A.1 and A.2 (apps. A–C are available online). It was shown in sections III.B and III.C that $h_0 \geq h^a(t)$ and $h_0 \geq h^{ma}(t)$ for $t \geq 0$, respectively. Conditions i and ii follow from the definition $\bar{h}^{mr} = h_0$. To prove condition iii, we show that $\dot{h}^a \leq \dot{h}^{ma}$ at any $h_0 \geq h \geq \bar{h}^a$. Condition iii then follows from $h^a(0) = h^{ma}(0) = h_0$. As shown in section III.B, $w^a(\bar{h}^a) = R/N$. For any $h \geq \bar{h}^a$, $w^a(h) \geq R/N$ by $dw^a/dh > 0$. Using equations (2) and (5), we write

$$\dot{h}^{ma} - \dot{h}^a = \theta(\bar{h}^{mr} - h) + (1 - \alpha)(Nw^a(h) - R). \tag{14}$$

This difference is positive from $\bar{h}^{mr} = h_0$ and $w^a(h) \geq R/N$, which establishes condition iii. It follows immediately from conditions i–iii and $dw^a/dh > 0$ that $w^a(h_0) \geq w^{ma}(t) \geq w^a(t)$ for $t \geq 0$. It remains to show that

$w^a(t) \geq w^{mr}(t)$ for $t \geq 0$. In section III.C, we showed that $w^{mr}(0) = R/N$ and $\dot{w}^{mr} \leq 0$, which implies $w^{mr}(t) \leq R/N$ for $t \geq 0$. We showed earlier that $w^a(t) \geq R/N$ for $t \geq 0$, and so condition iv is established.

IV. Empirical Strategy

This section draws on the theoretical results from section III to inform our empirical strategy. We first introduce our estimand of interest. We then propose a spatial RD estimator that exploits the spatially incomplete nature of groundwater rights over the Mojave aquifer. Theoretical predictions from section III inform the relationship between the spatial RD estimate and the estimand, what drives the RD estimate, and whether the RD estimate varies over time.

A. Causal Estimand

We are interested in whether the Mojave adjudication regime led to net benefits for landowners relative to a full open access counterfactual. For the population of parcels under adjudication, this is the difference in potential outcomes V^{mr} (see eq. [12]) and V^a (see eq. [3]). Our estimand of interest is the population average treatment effect:

$$\beta = \underbrace{\mathbb{E}_i[V_i^{mr} - V_i^a]}_{\gtreqless 0}, \tag{15}$$

where β is the average net benefit of adjudication relative to the full open access counterfactual. By proposition 1a, β is of unknown sign. The reason is that relative to a full open access regime, parcels under adjudication benefit from a higher water table and the ability to trade groundwater rights but also bear the cost of restricted pumping. Unfortunately, β cannot be directly estimated since V_i^{mr} and V_i^a are potential outcomes under counterfactual states and thus are not simultaneously observed (Holland 1986).

B. Spatial Regression Discontinuity Estimator

Instead, we consider a spatial RD estimator that exploits the boundary of the Mojave adjudication regime. Define d_i as parcel i's distance to the adjudication boundary. d_i is normalized so that a parcel is under adjudication when $d_i \geq 0$ (i.e., gray area within dark gray and light gray lines in fig. 2) and under open access when $d_i < 0$ (i.e., gray area outside dark gray and light gray lines in fig. 2). Our spatial RD estimator is

$$\begin{aligned}\hat{\beta}^{RD} &= \underset{d_i \downarrow 0}{\mathbb{E}}[V_i^{mr}] - \underset{d_i \uparrow 0}{\mathbb{E}}[V_i^{ma}] \\ &= \underbrace{\underset{i: d_i = 0}{\mathbb{E}}[V_i^{mr} - V_i^{ma}]}_{\gtreqless 0},\end{aligned} \tag{16}$$

where the first equality defines our spatial RD estimator at the adjudication boundary. The second equality uses the RD identifying assumption that expected land price under open access is continuous at the boundary, $d_i = 0$.[28] In particular, it implies that the water table height $h_i(d_i)$ and other unobserved characteristics are continuous at $d_i = 0$. While $\hat{\beta}^{RD}$ removes the effect of the water table, the remaining opposing influences of gains from groundwater rights trading and losses from pumping restrictions imply that $\hat{\beta}^{RD}$ remains of unknown sign, as indicated by proposition 1b.

How does $\hat{\beta}^{RD}$ relate to β? There are both internal and external validity considerations. Turning first to internal validity, let us denote the local β for parcels at the boundary as $\beta_{i:d_i=0}$. The difference between $\beta_{i:d_i=0}$ and $\hat{\beta}^{RD}$ is

$$\beta_{i:d_i=0} - \hat{\beta}^{RD} = \underbrace{\underset{i: d_i = 0}{\mathbb{E}}[(V_i^{mr} - V_i^{a}) - (V_i^{mr} - V_i^{ma})]}_{\geq 0},$$

which is weakly positive by proposition 1c. The RD estimator serves as a weak lower bound for the treatment effect at the boundary because it omits the benefit of a higher water table.[29] This lower bound argument can also be interpreted from the perspective of spillover effects. As our theory shows, in a spatially incomplete groundwater rights regime, water from the adjudicated area spills into the open access area, raising land prices for remaining open access parcels. Because this spillover benefit to open access parcels under adjudication would not occur under a full open access regime, the RD estimator produces a lower value than our estimand.[30]

The external validity of our RD estimate depends on the spatial structure of other land parcel characteristics. Water levels increase as one moves

[28] Specifically, following Hahn et al. (2001), the identifying assumption states that $\mathbb{E}[V_i^{ma}]$ is continuous in d_i at $d_i = 0$.

[29] Furthermore, it can be shown that an estimand defined as the average difference in land value between a spatially incomplete groundwater rights and open access regimes will be lower than that for a spatially complete groundwater rights regime. This is because there are no groundwater spillovers to open access areas when rights are complete. Thus, our RD estimate is also a weak lower bound on the net benefit of a spatially complete groundwater rights regime.

[30] Using the same argument, sec. VII.B shows RD evidence of groundwater well drilling in open access areas near the boundary following the introduction of adjudication, consistent with increased groundwater under adjudication that spills over into open access areas.

into the adjudication area away from the boundary. If other land parcel characteristics are uncorrelated with distance to the boundary, then by proposition 1d, the treatment effect at the boundary serves as a further lower bound for the treatment effect in the interior of the adjudication area. Thus, this orthogonality assumption, together with propositions 1c and 1d, implies that the spatial RD estimate is a lower bound for the population average net benefit: $\hat{\beta}^{RD} < \beta$.

Our theory also informs the various components of our spatial RD estimate. Specifically, using equations (12) and (13) and further allowing heterogeneity in water use (w_i^{mr}) and endowments (w_i^e) for adjudicated parcels and in water use (w_i^{ma}) for open access parcels, we can explicitly decompose $\hat{\beta}^{RD}$ into the following components (see appendix section A.6 for details):

$$\hat{\beta}^{RD} = \underbrace{\mathop{\mathbb{E}}_{i:\,d_i=0}\left[\int_0^\infty [\pi(w_i^e(s), h_i(s)) - \pi(w_i^{ma}(s), h_i(s))]e^{-\delta s}\,ds\right]}_{\leq 0 \text{ restriction cost}} + \underbrace{\mathop{\mathbb{E}}_{i:\,d_i=0}\left[\int_0^\infty \left[\pi(w_i^{mr}(s), h_i(s)) - \pi(w_i^e(s), h_i(s)) - p^w(s)(w_i^{mr}(s) - w_i^e(s))\right]e^{-\delta s}\,ds\right]}_{\geq 0 \text{ gains from trade}}. \tag{17}$$

$\hat{\beta}^{RD}$ is positive when the gains from groundwater rights trading offset the cost of restricted pumping.[31] In particular, for our RD sample of agricultural parcels, gains from trade would increase in parts of the aquifer with, among other features, expanding urban areas, whose demand for water drives up groundwater rights prices, allowing agricultural parcels to be net sellers of rights.

Finally, section III defines land prices at the start of the program, when $t = 0$ or in 1997. In this case, $\hat{\beta}^{RD}$ indicates whether landowners received a positive stream of discounted net benefits when the adjudication system was finalized. One may also be interested in whether continuation of the regime since 1997 has been economically justified. Our theory is agnostic on this matter: proposition 1e shows that the time derivative of the estimated effect at the boundary is of ambiguous sign. To test this, we examine RD effects for different periods after adjudication was introduced.

V. Data

Based on section III, the ideal outcome variable is parcel price, which bundles together the present discounted value of a parcel's land and water assets. Two proxy measures for parcel price are available in San Bernardino County: sales value and assessed value. Unfortunately, sales records in San

[31] For simplicity, our theory in sec. III ignores the small annual fee paid by landowners to administer the adjudication regime, set at around \$5 per acre-foot. Such fees provide another reason why $\hat{\beta}^{RD}$ serves as a lower bound.

Bernardino are not required to include the value of adjudicated groundwater rights when such rights are jointly transferred with a land parcel. This limitation rules out the direct use of sales data for our analysis.

By contrast, land value assessments in San Bernardino are required by law to include the value of adjudicated water rights attached to a land parcel. Specifically, when evaluating a parcel, the assessor is required to contact the Mojave Water Agency—which keeps a record of who owns groundwater rights, transfers, and the value of transfers—to determine a value that is inclusive of groundwater rights held by that parcel.[32]

For our primary data set, we use a single cross section of 2015 data containing parcel-level assessed land value, size, location, and the last year of sale, obtained from the San Bernardino County assessor. We impose several sample restrictions on this data set. First, we restrict attention to parcels that were last sold since 1997, after adjudication was confirmed by the county court and thus applied to all parcels within the boundary. Next, our RD design is applicable only to land parcels with access to underlying local groundwater. Thus, we exclude parcels that do not overlie the aquifer. We further exclude parcels in urban areas, as defined by the Federal Highway Administration, because their water comes from municipal water systems, not local groundwater pumping. We further webscraped a panel of annual assessed land values from 1976 to 2014 (but missing 1977) from an online data portal maintained by San Bernardino County. These data, however, do not include parcel covariates (such as size and year of last sale) and are thus used only in examining how RD effects evolve over time.

We further collect several auxiliary data sets. The US Geological Survey (USGS) digital elevation map provides parcel-level average slope and aspect (compass direction).[33] Well completion reports from the California Department of Water Resources provides the location, drilling year, and other characteristics of private groundwater wells. We use these data to construct a parcel-level measure of proximity to a private groundwater well as well as to examine the timing of well drilling near the adjudication boundary.[34] We use groundwater-level data from USGS monitoring wells to examine trend breaks in average Mojave groundwater levels. Last, we collect data on groundwater rights endowments, trading volumes, and prices from the Mojave Water Agency for various supporting analyses.[35]

Table C.1 (tables A.1, C.1 are available online) shows summary statistics for the variables in our primary data set. It includes parcels near the

[32] The assessor, however, does not separately report the value of water rights, only the combined value of a parcel's land and water assets.

[33] Available at https://viewer.nationalmap.gov/basic/.

[34] Available at https://data.ca.gov/dataset/well-completion-reports.

[35] Available at http://www.mojavewater.org/annual_report.html and http://www.mojavewater.org/water_transfer_reports.html.

adjudication boundary used in our RD estimation as well as more distant parcels.

VI. Results

This section presents our main RD result, robustness checks, and heterogeneity analyses.

A. *Specification*

To estimate our RD coefficient, $\hat{\beta}^{RD}$, from section IV.B, we follow Hahn et al. (2001) and model log land value for parcel i using a local polynomial regression

$$\ln V_i = \beta^{RD} R_i + f(d_i) + \theta' \mathbb{X}_i + \epsilon_i, \tag{18}$$

where, as in section IV.B, d_i is normalized distance to the adjudication boundary. $R_i = 1\{d_i \geq 0\}$ is an indicator variable equal to 1 when parcel i is in the adjudication area and 0 otherwise. $f(d_i)$ is a flexible local polynomial function that is fully interacted with R_i, allowing for different parameters on either side of the boundary. For example, under a linear specification, $f(d_i) = \alpha_1 + \alpha_2 d_i + \alpha_3 d_i R_i$. In some models, we include a vector of covariates, $\mathbb{X}_i$, detailed below. For our baseline specification, standard errors are clustered at the zip code level to allow for arbitrary forms of heteroscedasticity and spatial autocorrelation among land parcels within the same zip code.

Our RD coefficient of interest is $\hat{\beta}^{RD}$.[36] We report RD point estimates using a mean squared error (MSE) optimal bandwidth, which addresses the bias-variance trade-off inherent in RD bandwidth selection. However, inference based on the MSE-optimal bandwidth is generally invalid. We follow a recent econometrics literature that recommends reporting p-values and confidence intervals using an alternative robust bias correction procedure for bandwidth selection (Calonico, Cattaneo, and Titiunik 2014; Calonico et al. 2019).[37] In our baseline model, observations are uniformly weighted within bandwidths of equal length on both sides of the threshold. Robustness checks consider alternative bandwidths, error structures (including a zip code–level wild bootstrap procedure), and other estimation choices.

[36] Note that β^{RD} from eq. (18) is the RD effect in terms of log land values, whereas in eq. (16) it is defined in terms of (untransformed) land values.

[37] The use of different RD bandwidths for point estimation and inference implies reported confidence intervals that are not centered at reported point estimates.

B. Interpretation of RD Coefficient under Proposition 13

Interpretation of the RD coefficient in equation (18) requires a brief aside on how assessed land values are calculated in California. Since 1978, Proposition 13 has limited property tax increases across California by capping the annual appreciation rate of assessed land value at 2% following a parcel sale. Strong housing demand in southern California over recent decades means that this 2% limit has regularly constrained increases in assessed value. This implies that in any given year, the assessed land value of a previously transacted parcel likely captures its market price at the time of last sale, with a 2% annual adjustment.

There are two consequences of Proposition 13 that are germane to our RD analysis. First, for parcels last sold in 2015, the 2015 assessed land value equals its market value. Second, under certain conditions, we can use our single cross section of 2015 assessed land values, including parcels last sold since 1997, to recover an average RD effect across pooled 1997–2015 values. To see this, denote 2015 assessed log land value for parcel i as

$$\ln V_{i,2015} = \ln V_{i,2015-\tau_i} + r_i \tau_i,$$

where $\ln V_{i,2015-\tau_i}$ is parcel i's log value when it was sold τ_i years ago (i.e., in year $2015 - \tau_i$). r_i is the average annual land value growth rate between $2015 - \tau_i$ and 2015. If Proposition 13 always binds (i.e., $r_i = 0.02$ for all i), then provided that τ_i is continuous at the boundary, the outcome in equation (18) effectively becomes $\ln V_{i,2015-\tau_i}$, such that our RD estimate is a pooled average across 1997–2015 land values. If Proposition 13 does not always bind, our RD estimate still has a time-averaged interpretation, provided that the percentage change since last sale, $r_i \tau_i$, is continuous at the boundary.[38]

These two implications of Proposition 13 address concerns about the potential noisiness of assessed land values. In years when a parcel is not transacted, assessors typically determine the value of that parcel's land and groundwater assets by using market information from comparable land and groundwater transactions. These calculations can be noisy. While we remain unable to observe market (or true) values in years when a parcel is not transacted, Proposition 13 allows us to back out a parcel's market value in the year of its last sale despite using only a single cross section of assessed land values.

C. Covariate Smoothness

To assess the validity of our RD estimator, we begin by examining whether relevant covariates exhibit discontinuities at the adjudication boundary.

[38] Using our panel data set of land values, we calculate that Proposition 13's 2% annual cap was binding for 91% of parcel-year observations in our sample.

Our RD identifying assumption, introduced in section IV.B, requires that land prices under open access be continuous at the adjudication boundary. In some places, however, the boundary is defined according to the surface water drainage area of the Mojave River. Because the boundaries of a drainage area typically correspond to a local elevation peak, surface topological features may vary systematically across the boundary. For example, the slope of the land may change at the boundary. Likewise, the aspect of the land, or its compass direction and thus sunlight exposure, may also vary systematically at the boundary.[39] Both slope and aspect can influence a parcel's land value. Our identifying assumption also implies that groundwater levels be continuous at the boundary, which data limitations unfortunately prevent us from directly testing. Instead, we examine whether the presence of a privately drilled groundwater well within 1 mile of a parcel—which we view as an imperfect proxy for groundwater availability and possibly irrigation—jumps at the boundary.[40]

We also examine covariates that inform the interpretation of our RD coefficient. As discussed in section VI.B, our estimate would capture an average RD effect across 1997–2015 land values if there were no boundary jump in the year of last sale (in the case when Proposition 13 always binds) or in the percentage change in land value since last sale (in the case when Proposition 13 does not always bind). Finally, to ensure that our RD effect is not capturing differences in land value due to different parcel sizes, we also examine whether there is a discontinuity in land parcel size across the boundary.

Table 1 shows $\hat{\beta}^{RD}$ for each covariate, displayed across columns. Specifically, we estimate separate versions of equation (18), where each covariate in $\mathbb{X}_i$ serves as the dependent variable. Each model uses a local linear function for $f(d_i)$ and excludes other covariates as regressors. We do not detect statistically precise RD effects across these six covariates. In particular,

[39] We thank Jeff Vincent for this insight.

[40] Monitoring wells, which are specifically designed to measure groundwater levels, are spatially sparse in this part of California. For example, the calculation for average groundwater level in 2015 shown in fig. 1 was based on only nine monitoring wells. Spatial interpolations with such a small number of point measurements would generate imputed maps of groundwater levels that likely spatially vary more smoothly than the actual groundwater table and thus would be uninformative of groundwater levels at the boundary. Alternatively, California's Department of Water Resources well completion reports document privately drilled wells, which are far more spatially dense than monitoring wells. However, depth to well water for privately drilled wells varies with well characteristics and may not correspond to the true groundwater level. Furthermore, depth to well water is recorded only at the moment of initial drilling and not during the period when we observe land values. While we cannot use the well completion reports to measure groundwater levels, we use these data to determine whether a parcel is within 1 mile of a privately drilled well, which serves as a proxy measure for groundwater availability and possibly the presence of irrigation. We note, however, that the use of distance to construct this measure will necessarily impose some spatial continuity.

TABLE 1
Examining Covariate Smoothness

	Slope (1)	Aspect (2)	Near Well (3)	Last Sales Year (4)	Percent Change since Last Sale (5)	Size (6)
$\hat{\beta}^{RD}$	3.027	−21.510	.007	−1.034	25.587	3.383
p	.188	.929	.721	.184	.635	.181
95% confidence interval	−.833 to 4.23	−53.249 to 48.632	−.234 to .162	−2.91 to .559	−118.806 to 194.822	−4.675 to 24.823
Average open access value	1.858	150.759	.827	1,992.363	274.929	11.818
Observations	3,060	3,060	3,060	3,060	3,047	3,060
Zip codes	27	27	27	27	27	27

Note.—Estimates of β^{RD} are from eq. (18), with each covariate as the outcome. Specification includes a local linear model for $f(d_i)$ and excludes $\mathbb{X}_i$. Covariates are indicated across columns rows. Column 1 is average slope measured in degrees relative to level surface. Column 2 is average aspect measured in compass direction between 0° and 360°. Column 3 examines a dummy variable equal to 1 if a parcel is within 1 mile of a well. Column 4 examines the most recent year in which the parcel was sold. Column 5 examines a parcel's percentage change in value since its last sale. Column 6 examines parcel size in acres. Average covariate value for sample open access parcels is shown. Bandwidths are taken from the baseline log land value model in col. 1 of table 2. Observations are uniformly weighted. Standard errors are clustered at the zip code level.

absence of a discontinuity in the last year of sale and in the percentage change in land value since that year (cols. 4, 5) imply that our RD estimate on 2015 assessed land value reflects the average RD effect across the 1997–2015 period.

Figure B.2 plots binned average covariate values as a function of distance to the boundary to visualize the magnitudes of the RD effects in table 1 relative to covariate means in the open access area near the boundary. The only covariate whose noisy RD effect may have a meaningful magnitude is parcel slope. A potential discontinuity in slope is consistent with the surface water drainage basin defining a portion of the boundary, as land slopes need not be equal at the dividing line between two basins. However, the sign and magnitude of this jump in parcel slope should mitigate identification concerns. Prior hedonic studies find that measures of greater slope tend to lower agricultural land values, possibly through increased risk of soil erosion (Palmquist and Danielson 1989; Schlenker et al. 2005), but that the effect, when measured in degrees, tends to be small (Bigelow et al. 2017).[41] Thus, an RD effect on a slope of 3° implies an RD estimate on land values that is downward biased, but the magnitude

[41] Bigelow et al. (2017) find that a 1° increase in slope is correlated with a 1% decrease in agricultural land values. Applied to the RD effect on slope from col. 1 of table 1, this suggests a 3% decrease in agricultural land values. By contrast, our baseline RD effect on land values is 220%.

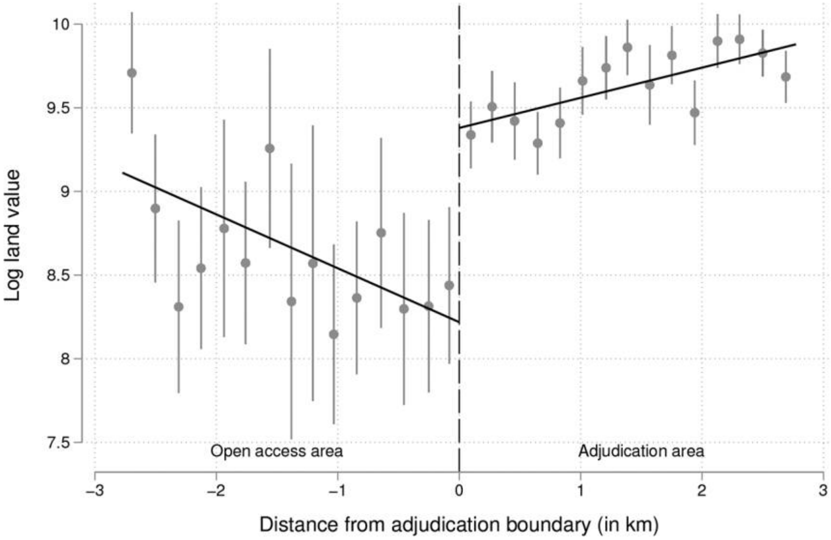


FIG. 4.—Graphical RD effect. Vertical axis shows log land value. Horizontal axis shows normalized distance d_i (in kilometers) to adjudication boundary, with $d_i \geq 0$ indicating the adjudication area and $d_i < 0$ indicating the open access area. Mean and 95% confidence intervals are shown for the outcome within equally spaced distance bins. Solid lines show linear functions fitted over unbinned data separately for each side of the boundary.

of the bias is likely small. In a robustness check, we include slope and other covariates as controls when estimating the RD effect on land values.

D. *Main RD Estimate and Robustness Checks*

We first present our main RD result graphically. Figure 4 plots log land value, our main outcome of interest, against distance to the adjudication boundary, d_i. We show log land value as local average means across different binned distances as well as fitted local linear functions within the MSE-optimal bandwidth, estimated separately for each side of the boundary. There is a clear jump in land values at the discontinuity.[42] We conduct a continuity test provided by Cattaneo et al. (2019), an alternative to the McCrary (2008) procedure that avoids prebinning data, and do

[42] Additionally, we find that land values are generally increasing from left to right when examining a wider bandwidth, as shown in fig. B.3. While this spatial pattern is not identified using our RD design, this is consistent with our theoretical prediction that groundwater levels rise as one moves from the open access area into the interior of the adjudication area.

TABLE 2
MAIN RD RESULTS (Outcome: Log Land Value)

	(1)	(2)	(3)	(4)
$\hat{\beta}^{RD}$	1.161	1.344	1.216	1.345
p	.019	.031	.008	.032
95% confidence interval	.207–2.32	.123–2.644	.322–2.196	.125–2.724
Percentage effect (%)	219	284	237	284
95% confidence interval	23–918	13–1,307	38–799	13–1,423
Polynomial order	1	2	1	1
Covariates	No	No	Yes	No
Last sales year	1997–2015	1997–2015	1997–2015	2015
Bandwidth	2.774	4.715	3.126	3.073
Observations	3,060	5,341	3,535	206
Zip codes	28	30	28	24

NOTE.—Estimates of β^{RD} are from eq. (18), with log land value as the outcome. Column 1 uses a local linear function for $f(d_i)$, excludes covariates, and includes all parcels that were last sold between 1997 and 2015. Column 2 uses a local quadratic function for $f(d_i)$. Column 3 includes a land parcel's average slope, average aspect, size, last sales year, and a dummy for whether the parcel is within 1 mile of a groundwater well as covariates. Column 4 restricts the sample to only parcels last sold in 2015. Point estimates use MSE-optimal bandwidth, with bandwidth reported. Inference is based on robust bias-corrected standard errors clustered at the zip code level, following Calonico, Cattaneo, and Titiunik (2014) and Calonico et al. (2019). Common bandwidths are employed on both sides of the threshold. Observations are uniformly weighted. Percentage effects are $100(e^{\hat{\beta}^{RD}} - 1)$.

not detect a discontinuity in the density of the distance variable at the threshold.[43]

We now turn to estimates of β^{RD} from equation (18), shown in table 2. For our baseline model, column 1 uses a local linear function for $f(d_i)$, excludes covariates, and includes all parcels last sold in the period 1997–2015. The statistically precise RD estimate of 1.161 translates to a 219% increase in land value. With mean land value for open access parcels within 1 km of the boundary at \$12,100, this implies a land value increase of \$26,500 (in 2015 dollars). To independently verify the magnitude of this effect, we compare this average land value increase with the average value of perpetual groundwater rights held by adjudicated parcels in our RD sample, which equation (17) indicates is an upper bound on our RD estimate (see appendix section A.7 for details). In 2015, this value was \$195,000.

The rest of table 2 offers several robustness checks. Column 2 models $f(d_i)$ using a local quadratic model. To address remaining concerns about

[43] We further note that traditional RD sorting concerns are lessened in our context. First, land parcels are fixed in space. Second, although there could be unobserved preference heterogeneity among landowners (e.g., some landowners may strongly prefer parcels with secure rights to water), competition in the land market implies that the value of an individual parcel's attributes is determined by the aggregate distribution of preferences across the market and not by individual preferences of that parcel's buyer and seller (Rosen 1974).

TABLE 3
Robustness: Alternative Bandwidths (Outcome: Log Land Value)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\hat{\beta}^{RD}$	1.161	.963	.836	1.028	1.042	.838	.935
p	.019	.000	.000	.013	.038	.007	.009
95% confidence interval	.207–2.32	.948–1.969	.555–1.733	.181–1.548	.067–2.353	.36–2.296	.273–1.884
Bandwidth	2.774	1.000	1.500	2.000	4.000	5.000	6.000
Observations	3,060	1,054	1,571	2,110	4,545	5,606	6,566
Zip codes	28	23	25	26	27	27	29

Note.—Estimates of β^{RD} are from eq. (18), with log land value as the outcome. All models use a local linear model for $f(d_i)$, exclude covariates, and uniformly weights observations. Column 1 replicates the baseline model in col. 1 of table 2. Columns 2–7 use narrower and wider bandwidths, imposing the same bandwidth for point estimates and zip code–clustered standard errors. Common bandwidths are employed on both sides of the threshold. Observations are uniformly weighted.

potentially large—though imprecise—jumps in the covariates examined in table 1, column 3 augments our baseline specification by including these covariates.[44] Last, to examine parcels whose assessed value equals the sales value, column 4 restricts our sample to parcels transacted in 2015. All three robustness checks detect positive and statistically significant RD effects that are similar in magnitude to our baseline result in column 1.

We next consider several additional robustness checks to the baseline result in column 1 of table 2. Table 3 presents RD estimates using bandwidths smaller than one-half and larger than twice that of the baseline MSE-optimal bandwidth, showing also the number of parcels at different bandwidths around the boundary. Our RD result is not sensitive to these different bandwidth sizes.

Table C.2 considers various error structures and variance estimation procedures. Our main RD sample uses zip code–clustered standard errors with 28 zip codes. To address potential issues with having few clusters (Cameron et al. 2008), column 2 conducts a zip code–level wild bootstrap procedure specific for RD designs, following He and Bartalotti (2020). This has little influence on the precision of our RD estimate. We further show in columns 3–6 that our RD result is insensitive to whether variance estimation is undertaken using zip code–level clustering, nearest neighbor matching, or both. Column 7 shows that our RD result also holds when applying a local randomization method that allows for exact inference in finite samples but requires the additional assumption that potential outcomes are nonrandom (Cattaneo et al. 2015, 2016).

[44] Column 3 of table 2 includes all covariates shown in table 1 except for the percentage change in land value since last sale because that variable is constructed using assessed 2015 land value, our outcome of interest in table 2.

In table C.3, we estimate the RD coefficient allowing the MSE-optimal bandwidth to differ on both sides of the discontinuity and consider bandwidths that are coverage error rate optimal (Calonico, Cattaneo, and Farrell 2019). We also alternatively weight observations using a triangular (rather than a uniform) kernel. Our results are stable across these bandwidth selection choices.

Finally, table 4 conducts placebo tests by estimating RD effects using alternative locations for the boundary. Because there is no actual spatial discontinuity between adjudication and open access regimes across these placebo boundaries, we should not detect any RD effects. For models in columns 1–3, we create false boundaries that are 9, 6, and 3 kilometers, respectively, within the open access area relative to the real boundary. In columns 4–6, we create similarly spaced false boundaries within the adjudication area. We do not detect RD effects using any of these false boundaries.

E. *Heterogeneity*

We now turn to heterogeneity analyses across time and space. Our main RD estimate using 2015 assessed land values pools parcels that were last sold within the 1997–2015 period. The presence of Proposition 13—together with columns 5 and 6 of table 1 showing no boundary discontinuity in the last year of sale or the percentage change in land value since last sale—suggests that our main RD estimate reflects the average RD effect over the 1997–2015 period rather than the effect for only 2015. A natural question then is whether this effect has changed since the program was introduced,

TABLE 4

Placebo Boundary Tests (Outcome: Log Land Value)

	(1)	(2)	(3)	(4)	(5)	(6)
$\hat{\beta}^{RD}$	.014	−.092	.028	−.191	.052	−.036
p	.640	.867	.995	.493	.755	.739
95% confidence interval	−1.098 to .675	−1.177 to .992	−1.655 to 1.645	−.892 to .43	−.379 to .522	−.697 to .494
Distance to true boundary (km)	−9	−6	−3	3	6	9
Bandwidth	2.274	2.410	6.185	3.748	3.213	3.495
Observations	218	449	4,183	6,585	6,311	6,523
Zip codes	10	22	23	33	31	32

Note.—Estimates of β^{RD} are from eq. (18), with log land value as the outcome. All models use a local linear model for $f(d_i)$ and exclude covariates. Columns use placebo boundaries set 9, 6, and 3 kilometers within the open access (i.e., $d_i < 0$) and adjudication areas (i.e., $d_i \geq 0$). Point estimates use MSE-optimal bandwidth, with bandwidth reported. Inference is based on robust bias-corrected standard errors clustered at the zip code level, following Calonico, Cattaneo, and Titiunik (2014). Common bandwidths are employed on both sides of the threshold. Observations are uniformly weighted.

TABLE 5
HETEROGENEITY ACROSS TIME (Outcome: Log Land Value)

	(1)	(2)	(3)	(4)	(5)
$\hat{\beta}^{RD}$	.427	.696	1.728	1.176	1.159
p	.253	.155	.045	.041	.065
95% confidence interval	−.25 to .949	−.22 to 1.379	.042 to 3.797	.049 to 2.225	−.069 to 2.296
Sample period	1976–79	1980–89	1990–96	1997–2005	2006–14
Bandwidth	1.157	1.525	2.170	1.689	2.141
Observations	1,065	1,887	715	662	932
Zip codes	21	22	21	21	21

NOTE.—Estimates of β^{RD} are from eq. (18), with log land value as the outcome from a panel of assessed land values between 1976 and 2014 (missing 1977). Each model is estimated over different indicated time intervals. All models use a local linear model for $f(d_i)$ and exclude covariates. Point estimates use MSE-optimal bandwidth, with bandwidth reported. Inference is based on robust bias-corrected standard errors clustered at the zip code level, following Calonico, Cattaneo, and Titiunik (2014). Common bandwidths are employed on both sides of the threshold. Observations are uniformly weighted.

which proposition 1e indicates is ambiguously signed. Another related question is: what is the magnitude of the RD effect before 1997?

To shed light on these questions, we turn to our panel of annual assessed land values covering the 1976–2014 period. Table 5 reports RD estimates from equation (18) estimated separately across various time periods.[45] Three results from table 5 are worth noting. First, the RD estimate has changed very little since the introduction of adjudication, as shown in columns 4 and 5.[46] That our estimates remain positive across time suggests that the continuation of adjudication has been economically justified. Second, we detect a statistically precise RD effect in the early 1990s. Because a subset of users already faced adjudication starting in 1993, these effects reflect a combination of implemented and anticipated RD effects. Third, as columns 1 and 2 show, in the period before the adjudication process began, the RD effect was smaller than the postadjudication RD effect

[45] We are interested in the time evolution of land values since 1976. However, because of Proposition 13, land values of parcels not sold in a given assessment year are likely to capture values during the year of last sale and not values during the year of assessment. Including parcels sold prior to the assessment year would result in an artificially smoothed RD estimate over time. Unlike our main data set of 2015 land values obtained from the land assessor, we are unable to drop parcels from our webscraped panel data set that were transacted earlier because this data set does not explicitly contain information on year of last sale. To address this, the estimating samples in table 5 attempt to detect parcels sold during the assessment year by including only parcels for which there is a change in owner name that year or for which the growth rate in assessed land value exceeded 2%.

[46] Following n. 45, because we need to infer when parcels were sold in our panel data set, the estimating sample (and thus RD estimates) in cols. 4 and 5 of table 5 differs slightly from that of our main RD estimate in table 2 using 2015 assessed land values for which we observe year of last sale.

and not statistically significant. In particular, the 1976–79 RD effect was roughly 37% of the post-1996 RD effect (see fig. B.4 for a graphical RD presentation on 1976–79 land values).

There are two explanations for the smaller noisy RD effects prior to the 1990s. First, recall that there was an earlier failed attempt at adjudication during 1966–76 and discussions over future adjudication continued through the 1970s and 1980s. Because those earlier proposals also foresaw management by the Mojave Water Agency, whose spatial boundaries are largely unchanged since 1960, any anticipation from an eventual adjudication could be capitalized in pre-1990 land values. A second explanation is that the pre-1990 RD effect captures a time-invariant jump in land values at the boundary that has nothing to do with the groundwater market. If so, this bias would show up in both pre-1990 and post-1990 RD estimates. In the presence of these two possibly concurrent explanations, one can look at the difference in RD estimates between columns 1 and 5 of table 5, the two bookend periods of our panel data set. This difference, which equals 0.73 but is not statistically precise, would remove any potential time-invariant bias. In the absence of any anticipated effects prior to 1990, this difference captures the true RD effect. In the presence of anticipated effects, this difference captures a lower bound on the true RD effect, where the bound is determined by the probability of eventual adjudication anticipated during the earlier period.[47]

Section IV.B discusses how our spatial RD estimate depends on the market value of water. When this outside value is high, tradeable groundwater rights allow agricultural landowners to gain from selling rights to other users overlying the aquifer. For groundwater in the Mojave, this higher-value use is likely strongest in the more urban southern part of the region (see inset map in fig. 2).

To test whether urban water demand creates larger net benefits, table 6 examines heterogeneity in the RD coefficient for the southern and northern subareas. Because rights trading can occur only within a particular subarea, one would expect the RD effect to be larger in the more urbanized southern subareas, all else equal. Column 1 replicates our baseline results. The model in column 2 restricts the sample to parcels in the southern subareas, while only northern subareas parcels are used to produce estimates in column 3. The RD coefficient for the southern subareas is almost five times larger than for the northern subareas, though statistical inference is complicated by the limited number of zip code clusters.

[47] To see this, denote $\hat{\beta}^{RD}_{pre}$ and $\hat{\beta}^{RD}_{post}$ as the RD estimates from cols. 1 and 5 of table 5 and β^{RD} as the true RD effect of adjudication. Let γ be time-invariant bias in the estimates and $\vartheta \in [0, 1]$ be the probability during the preadjudication period that adjudication would eventually be implemented, such that $\hat{\beta}^{RD}_{pre} = \vartheta\beta^{RD} + \gamma$ and $\hat{\beta}^{RD}_{post} = \beta^{RD} + \gamma$. If eventual adjudication was not anticipated in this earlier period (i.e., $\vartheta = 0$), then $\hat{\beta}^{RD}_{post} - \hat{\beta}^{RD}_{pre} = \beta^{RD}$. If there was any anticipation (i.e., $\vartheta > 0$), then $\hat{\beta}^{RD}_{post} - \hat{\beta}^{RD}_{pre} = \beta^{RD}(1 - \vartheta) < \beta^{RD}$.

TABLE 6
Heterogeneity across Space (Outcome: Log Land Value)

	(1)	(2)	(3)	(4)	(5)	(6)
$\hat{\beta}^{RD}$	1.161	1.784	.374	1.175	.332	1.325
p	.019	.023	.495	.224	.469	.007
95% confidence interval	.207 to 2.32	.269 to 3.614	−.616 to 1.274	−.802 to 3.419	−.481 to 1.046	.409 to 2.514
Area	All	South	North	South	North	Drop along LA
Boundary definition	All	All	All	MWA	MWA	All
Observations	3,060	2,260	800	2,078	318	1,772
Zip codes	28	17	14	13	13	28

Note.—Estimates of β^{RD} are from eq. (18), with log land value as outcome. All models use a local linear model for $f(d_i)$ and exclude covariates. Column 1 replicates the baseline model in col. 1 of table 2. Columns 2 and 3 restrict the sample to land parcels in southern and northern subareas, respectively. Columns 4 and 5 further restrict the southern and northern subarea samples, respectively, by including only parcels whose nearest boundary is defined by the Mojave Water Agency (MWA). Bandwidths are taken from the baseline log land value model in col. 1 of table 2. Observations are uniformly weighted. Standard errors are clustered at the zip code level. LA = Los Angeles.

As an alternative approach to modeling this heterogeneity, we interact R_i and $f(d_i)$ from our baseline model in equation (18) with a parcel's latitude. Figure B.5 plots how $\hat{\beta}^{RD}$ varies as one moves northward over the aquifer, showing a statistically significant decline. For parcels that are farthest north, the RD effect becomes negative, which is possible when the gain from trading rights is small.[48]

How much does the tradeability of groundwater rights contribute to the net benefit of the Mojave adjudication regime? Columns 1–3 of table 6 merely show that gains from rights trading contribute to the net benefit but not by how much. Note also that by controlling for groundwater level differences, our RD approach cannot definitively isolate the gains from groundwater trading. To conduct a back-of-the-envelope calculation, we assume that the benefit of a higher groundwater table can be identified using land value differences farther away from the boundary and that the gains from rights trading in the northern subareas is small. With these assumptions, we calculate that rights trading contributes to at most 39% of

[48] While the largest RD estimates occur in subareas with more municipalities, we also observe transaction of rights between agricultural users, as represented by our theory in sec. III. In particular, of all perpetual rights transactions in the period 1997–2015, 23% were between agricultural landowners and municipalities, and 77% were between agricultural users. During that same period, of all transactions of annual leases to rights, 48% were between agricultural landowners and municipalities, 45% were between agricultural landowners, and 7% were between municipalities.

the net benefit of the Mojave adjudication regime, though this estimate is highly uncertain.[49]

Table 6 also shows two final robustness checks. The RD effect may be heterogeneous depending on how the boundary is defined. The model in column 4 of table 6 further restricts the sample of southern subarea parcels to those whose nearest boundary is defined by the spatial extent of the Mojave Water Agency (light gray line segments in fig. 2) and not by the Mojave River drainage basin (dark gray line segments in fig. 2). Column 5 uses a similar sample restriction for the northern subareas. Our RD effect does not differ greatly by how the boundary is defined.[50] Finally, column 6 shows that our RD effect is robust to dropping parcels that are in the subarea directly adjacent to Los Angeles County.[51]

VII. Aggregate Net Benefit of Adjudication

We now turn to quantifying the aggregate net benefit of adjudication. We first use RD estimates from section VI to quantify the aggregate net benefit to agricultural parcels and then provide a back-of-the-envelope calculation for the aggregate net benefit to urban areas. Both values are potential

[49] To obtain 39%, we divide the difference between RD estimates in cols. 1 and 3 of table 6 (i.e., 1.16–0.37), which isolates the gains from rights trading, by the difference in average land values at the edge of the support shown in fig. B.3 (i.e., 9.85–7.81), which incorporates the water table gradient. This is an upper bound on the contribution of rights trading because gains from trading in the northern subareas, while smaller, are still positive (i.e., the true numerator is smaller) and because the true water table difference is likely larger (i.e., the true denominator is larger). Monte Carlo simulations using the robust bias-corrected inference statistics associated with cols. 1 and 3 of table 6 produces a 95% confidence interval of −24% to 128%. This large uncertainty suggests that this back-of-the-envelope calculation should be interpreted with caution.

[50] Figure 2 shows that boundary segments defined by the Mojave Water Agency (light gray line segments) are better represented in the southern parts of the adjudication area. Thus, an RD estimate using all parcels near the Mojave Water Agency boundary would have more southern subarea parcels and would not be comparable to an RD estimate using all parcels near the Mojave River drainage basin boundary. Table 6 addresses this by examining whether RD estimates differ by boundary definition separately for northern and southern subsamples. Alternatively, we also follow Gerardino et al. (2017) by running an RD subsample test that weights all parcels by their latitude and do not find RD estimates that differ by boundary definition.

[51] Furthermore, within our RD sample there are no open access parcels that fall under the jurisdiction of a different water agency. This implies that for parcels near the Mojave Water Agency boundary, those that were adjudicated were under Mojave Water Agency jurisdiction, while open access parcels were not part of any local water agency. Because the primary benefit of the Mojave Water Agency is groundwater access, we do not anticipate that this institutional difference results in discontinuities in nonadjudication Mojave Water Agency benefits at the boundary. However, because Mojave Water Agency parcels have to pay an annual fee of 16.75 cents per $100 of assessed land value to the Mojave Water Agency for services aside from the adjudication, the presence of this fee may bias our RD estimate downward. We believe that the magnitude of this bias is small, as this fee amounts to $23.95 for the average adjudicated land parcel in our sample, which is negligible relative to our estimated coefficient.

lower bounds because they hold groundwater levels fixed. To explore whether adjudication led to more groundwater, we present three additional pieces of evidence implying that Mojave groundwater levels increased as a consequence of adjudication.

A. *Quantifying a (Lower Bound) Aggregate Net Benefit*

We first quantify the aggregate net benefit of the Mojave adjudication regime for agricultural parcels. Proposition 1c states that our RD estimate is a lower bound on the local average treatment effect for agricultural parcels at the boundary. If one further assumes that other parcel characteristics are uncorrelated with distance to the boundary, proposition 1d states that the local average treatment effect at the boundary is itself a lower bound for the population average treatment effect across all agricultural parcels. This orthogonality assumption, together with the south-north heterogeneity in the RD coefficient, enables a lower bound calculation for the aggregate net benefit of adjudication across agricultural parcels.

To that end, we multiply the heterogeneous RD effect separately for agricultural parcels in southern (i.e., col. 2 of table 6) and northern (i.e., col. 3 of table 6) subareas with each parcel's land value. We then sum this product across all adjudicated agricultural parcels. This results in a value of $350 million (in 2015 dollars), or a 40% increase in total land value.[52]

Water access for urban areas is not tied to underlying groundwater but rather comes from municipal water systems. While this means we are unable to apply our spatial RD estimator to urban areas, appendix section A.8 details how an extension of our theory along with data on aggregate urban water allocation and trade combine to quantify the aggregate net benefit to urban areas. Our calculation is based on the following argument: unlike agricultural parcels, municipalities supplying water to urban areas held lower priority access to groundwater prior to adjudication and were likely pumping below their private optimum. If, following adjudication, one observed an increase in aggregate urban water consumption, the gain from increased water use must exceed the cost of purchasing groundwater rights from agricultural parcels, implying a positive aggregate urban net benefit. In appendix section A.8, we calculate for a range of demand elasticities found in the literature that adjudication resulted in an aggregate net benefit in the range of $72–$131 million (in 2015 dollars) for urban areas. Altogether, the aggregate net benefit to agricultural and urban areas of the groundwater market is $422–$481 million. By comparison, administrative

[52] Unlike the 219% average RD sample increase calculated in col. 1 of table 2, this aggregate percentage increase takes into account heterogeneity in RD estimates between northern and southern subareas and the number of parcels and their values in each region. Because there are many more parcels in the northern subareas where the RD effect is lower, the aggregate effect is weighted toward the northern RD effect.

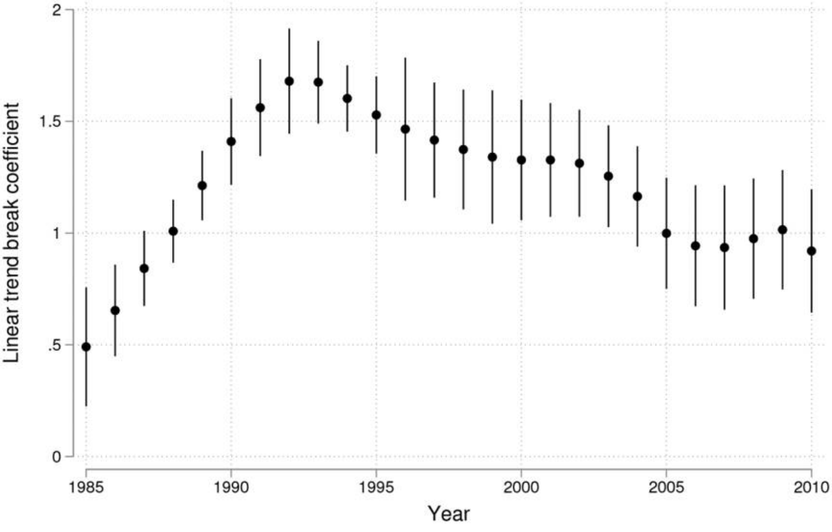


FIG. 5.—Trend breaks in average Mojave groundwater levels. The figure shows the trend break coefficient κ_2 and its 95% confidence interval from the model: $h_t = \kappa_1 t + \kappa_2 t\mathbf{1}\{t \geq \bar{t}\} + \kappa_3 \mathbf{1}\{t \geq \bar{t}\} + \mu_t$, where t is year, h_t is average Mojave groundwater levels (plotted in fig. 1), μ_t is an error term that is robust to serial correlation and heteroscedasticity with optimal bandwidth (following Newey and West 1987), and $\bar{t}$ is the imposed trend break, which varies across years 1985–2010 (shown on x-axis). Sample period is 1980–2015, the years with continuously available average Mojave groundwater levels.

and legal costs to set up the adjudication system during the 1990s was \$40 million (in 2015 dollars; Figueroa 2001).[53]

B. *Did Adjudication Increase Groundwater Levels?*

The aggregate net benefit estimates in section VII.A omit any benefits of a higher groundwater table. If groundwater levels increased under the adjudication, these values are a strict lower bound on the net private and social benefits of the policy. If groundwater levels did not change, then the benefit of adjudication derives only from a more efficient allocation of that groundwater. We turn to three pieces of evidence beyond our main RD result to examine whether adjudication increased groundwater levels relative to the open access counterfactual.

First, we return to the time series of average Mojave groundwater levels depicted in figure 1, which shows groundwater levels stabilizing in recent decades. To examine the timing of this trend break in groundwater levels, figure 5 plots trend break coefficients from separate regression models in

[53] This value may understate total setup costs if there were efforts to increase the likelihood of adjudication prior to the 1990s. Unfortunately, related cost figures are not available.

which the timing of the imposed linear trend break varies across years between 1985 and 2010. We detect the largest trend break in average Mojave groundwater levels around 1993, the year in which 75% of groundwater users first adopted pumping restrictions. One concern with interpreting this trend break as causal evidence is that, as the theory in section III.B details, groundwater levels would have also eventually stabilized had the prior open access regime continued. It is possible that stabilization under open access also would have occurred in 1993.[54]

To rule out this possibility, for our second piece of evidence we return to our spatial RD setting and look at the timing of when wells were drilled. If adjudication did not result in more groundwater compared with the open access counterfactual, one would not observe changes in efforts to access water following the introduction of adjudication. Table 7 replaces the outcome in equation (18) with a dummy variable for whether a groundwater well was drilled during or after 1993, the year when most groundwater users were first subject to pumping restrictions. The negative RD coefficient in column 1 indicates that there are more wells drilled since 1993 just inside the open access area than just inside the adjudication area. Columns 2 and 3 show that this discontinuity is not present for placebo boundaries placed 3 kilometers within the open access and adjudication areas. More wells since 1993 on the open access side is consistent with the pumping restrictions imposed by the adjudication increasing groundwater spillovers into the open access area, lowering the cost of pumping, and increasing the returns to drilling a well on unrestricted open access parcels.[55]

Our final argument turns to the price of groundwater rights. Figure B.7 plots the average traded prices of perpetual rights and annual leases under the Mojave adjudication regime during the 1997–2015 period, showing consistent trading at positive prices. As discussed in section III.C, heterogeneous endowments produce initial differences among landowners in the shadow value of water λ^{mr}. These differences imply gains from trade, which are exhausted when λ^{mr} is equal across all landowners and equal to the competitive price for a water right. Thus, a positive price for water implies a positive shadow value for all landowners and water use w^{mr} that

[54] A second concern may be that the Mojave Water Agency began recharging the aquifer with water deliveries from California's State Water Project in 1990. While this does not invalidate our RD design, which excludes changes in groundwater levels, it may prohibit one from drawing causal conclusions from the time break analysis in fig. 5. However, as fig. B.6 shows, there is no clear trend break in State Water Project deliveries in 1993.

[55] The only way for more open access wells after adjudication to not imply increased groundwater levels is if adjudication required adjudicated parcels to pump more than they would have under open access. Under this circumstance, one can construct a scenario whereby groundwater levels are lower in the adjudicated area and higher in the open access area following adjudication such that there is no change in total groundwater compared with full open access. We think this is highly unlikely, particularly since agricultural users were already pumping at their private optimum prior to adjudication such that any mandate to pump more would have led to private losses for all adjudicated users.

TABLE 7
RD EFFECT ON WHETHER WELL WAS DRILLED SINCE 1993

	(1)	(2)	(3)
$\hat{\beta}^{RD}$	−.188	.045	.049
p	.041	.892	.402
95% confidence interval	−.468 to −.01	−.292 to .335	−.087 to .217
Distance to true boundary (km)	0	−3	3
Bandwidth	7.400	5.756	6.947
Observations	1,009	238	1,828
Zip codes	26	23	31

NOTE.—Estimates of β^{RD} are from eq. (18), with a dummy variable for whether a groundwater well was built since 1993 as the outcome. All models use a local linear model for $f(d_i)$ and exclude covariates. Column 1 uses the true adjudication boundary. Columns 2 and 3 use placebo boundaries set at 3 kilometers within the open access (i.e., $d_i < 0$) and adjudication areas (i.e., $d_i \geq 0$). Point estimates use MSE-optimal bandwidth, with bandwidth reported. Inference is based on robust bias-corrected standard errors clustered at the zip code level, following Calonico, Cattaneo, and Titiunik (2014). Common bandwidths are employed on both sides of the threshold. Observations are uniformly weighted.

satisfies $\partial\pi/\partial w = \lambda^{mr} = p^w > 0$. The properties of π—concave and single peaked in w—imply $\partial\pi/\partial w > 0$ if and only if $w^{mr} < w^a$ since w^a satisfies $\partial\pi/\partial w = 0$. The same argument holds for the price of a perpetual groundwater right. In sum, positive water prices are a sufficient condition for the adjudication to have reduced pumping relative to open access and thereby increased groundwater levels.

These three additional pieces of evidence all suggest that adjudication resulted in more groundwater than would have occurred under the open access counterfactual. As such, it is likely that adjudication resulted in social benefits by reducing the externality associated with groundwater pumping. Furthermore, this implies that the aggregate net benefit of adjudication calculated in section VII.A, which omits the benefit from more groundwater, is understated.

VIII. Conclusion

This paper applies a spatial RD design to quantify the net benefit of using an environmental market to manage a groundwater aquifer in southern California. We estimate that agricultural land values on the groundwater market side of the boundary are on average 220% higher than on the open access side. Using a model of dynamic groundwater extraction, we show that our RD estimate corresponds to a weak lower bound on the net benefit of the program for agricultural parcels. Heterogeneity analyses suggest that a component of these benefits comes from the tradeability of these rights, which enable a more efficient allocation of water away from water-intensive agriculture toward urban use. Furthermore, additional evidence suggests that the groundwater market led to increased groundwater levels.

Our findings can inform efforts to address overextraction of other common-pool resources, such as fisheries, forests, and the global climate. For groundwater in particular, California recently passed the Sustainable Groundwater Management Act, an unprecedented policy requiring users of overextracted aquifers to adopt sustainable management plans. While it remains contentious which management tools should be employed, this paper's findings suggest that a market for groundwater rights can lead to substantial net benefits. Users and regulators alike may reference these benefits in future efforts to establish environmental markets for groundwater and common-pool resources more generally.

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PUBLIC POLICY INSTITUTE OF CALIFORNIA

Improving California's Water Market

How Water Trading and Banking Can Support Groundwater Management

Technical Appendix C. Mojave Groundwater Market Assessment

Andrew Ayres

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Introduction

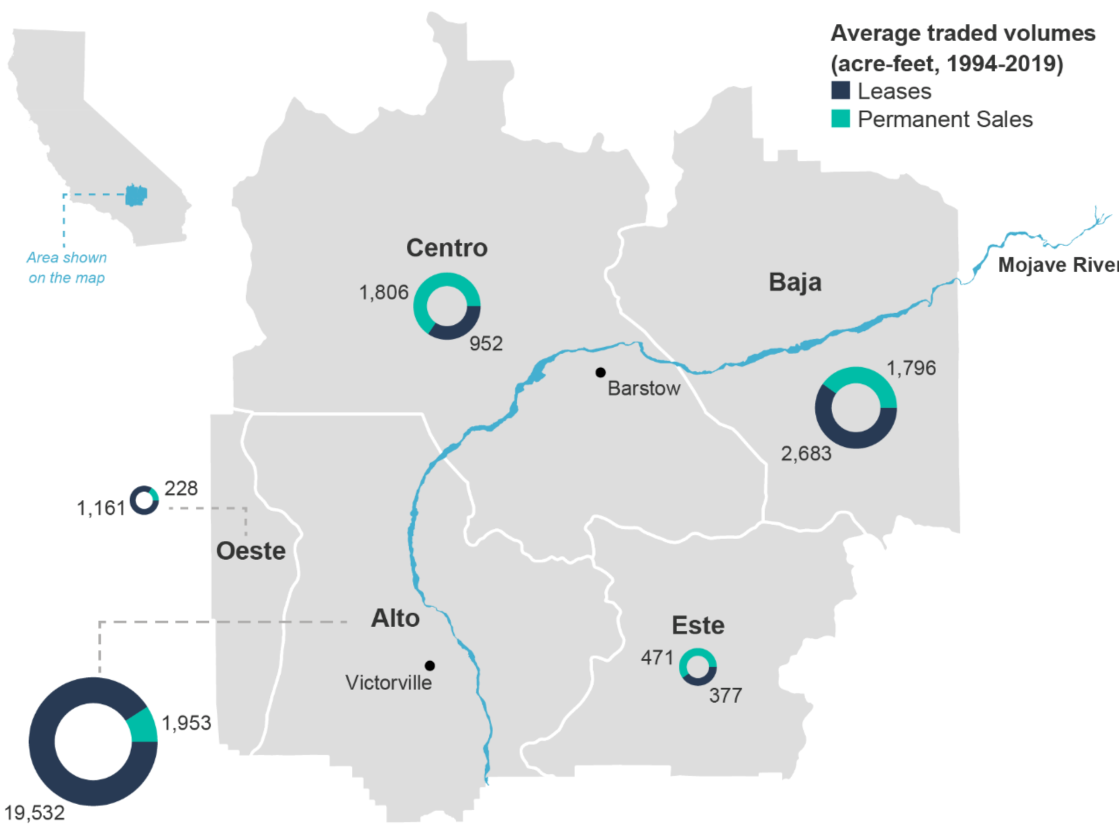
This appendix documents trading activity in the Mojave groundwater market and investigates how the market has provided a platform to resolve shared water management challenges. In the 1990s, water users in the western Mojave Desert undertook a court adjudication process that would redefine groundwater rights and create a market to trade those rights. Today, the Mojave's is one of the most liquid groundwater markets in California. This market provides real value to water users: a recent analysis suggests that over $400 million in economic gains have resulted from the adjudication (Ayres et al., 2021).

Background

Figure C1 presents the adjudicated area of the Mojave, delineates the subareas that make up distinct groundwater markets, and provides measures of average trading volumes. Aside from agricultural and other undeveloped lands, this area includes the cities of Victorville, Hesperia, and Barstow. The Mojave River drains the north side of the San Bernardino Mountains and represents a major source of native groundwater recharge. Imports from the State Water Project have also recharged the basin since 1990.

FIGURE C1

The Mojave's subareas have lease and sale markets with varying levels of activity



SOURCE: Author calculations using data from Mojave Watermaster. Boundary designations from watermaster.

NOTE: The Mojave adjudicated area in gray, with its subareas outlined. Circles are sized by 2014-15 production, and report annual averages for water leased (blue; FPA) and sold (green; BAP) in acre-feet per year. Data from water years 1994-95 to 2018-19.

The Mojave groundwater market is not truly one market, but instead a collection of several. Certain regions, or subareas, in the adjudicated zone exhibit greater hydrologic connection within themselves than they do with other areas. A trade that moves pumping rights from one area into another would result in an increase in total pumping—and consumptive use—in the receiving subarea that could set it out of long-term hydrologic balance. Such transfers are prohibited outside of exceptional cases requiring watermaster approval, so five separate markets have emerged.

Each year, hundreds of trades take place—mostly one-time annual leases of production allowance, but also permanent transfers of rights to pump year after year. Groundwater pumping rights were defined volumetrically and allocated based on pumping during the five-year period immediately prior to adjudication (1986-1990); they are commonly referred to as Base Annual Production rights (BAP). Each year, each acre-foot of BAP generates Free Production Allowance (FPA), which entitles a holder of FPA to pump a specified amount of water. Where a pumper exceeds his or her allocation in any given year, the difference must be offset: options include leasing FPA from other users, purchasing replenishment water (imported via the SWP) from the watermaster, and using carryover FPA from previous years.

Several features of the Mojave groundwater market warrant description. First, carryover of FPA is allowed—but only for one year. A unit of FPA that goes unused in the year it is generated may be carried over to the next year; however, it can no longer be used for pumping in the year after that. (Other adjudicated basins adopt similar limitations to avoid concentrated pumping impacts in any given year.) The ability to carry over aids water users in managing variable demands, and carried-over FPA may be transferred in the same manner as current-year FPA.

Second, because the adjudication allocated rights according to the pre-adjudication pumping regime, and the basin was in a state of overdraft at the time, in order to move total extraction in each subarea toward safe yield—and ultimately bring the subareas into balance—the FPA return on BAP has declined over time. Allocations of FPA began at 100 percent of BAP and were planned to ramp down to 80 percent over the first five years, with the watermaster assessing evidence of continued overdraft to recommend additional ramp-down in years thereafter. Some subareas have seen additional ramp-down; for example, in Baja, the 2020-21 FPA yield was 25 percent. In the interim, some "transitional pumping" has occurred, generating additional drawdown. Many users are contemplating similar approaches under SGMA. In Mojave, rights to pump this transitional water have been tradable, which has helped to simplify administration, allocate the transitional water efficiently, and expand the set of assets pumpers can flexibly monetize.

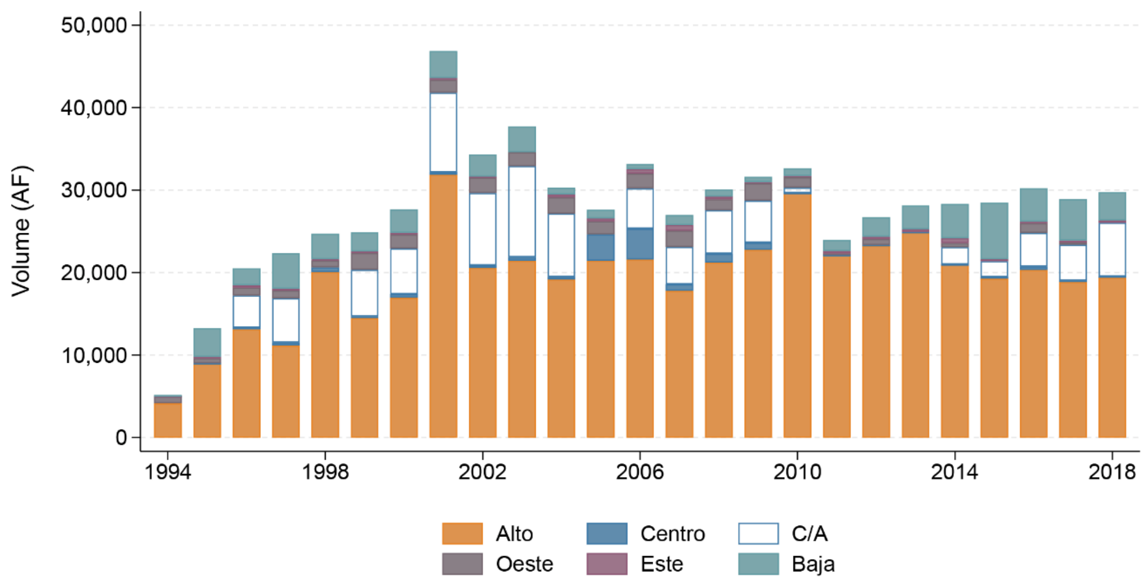
Finally, inter-subarea trading, despite being prohibited in most cases, is regularly allowed for one purpose. When insufficient water flows from the Alto subarea to the Centro subarea, pumpers in Alto incur a make-up obligation. This can be met either by paying the watermaster for imported water or by purchasing FPA from Centro pumpers. The final section of this appendix evaluates the benefits of resolving this management issue using markets.

Market Activity

Figures C2 and C3 jointly capture the dynamics of the Mojave's various water markets. Trading in the Alto subarea makes up the lion's share of market activity, and it sees the highest prices for water. The Baja subarea in the northeastern area of the Mojave sees the second-highest trading volume. Trading activity in the Este subarea is low, as there are few pumpers and water needs on the spot market are rare, in part because there has been limited ramp-down and in part because water uses tend to be similar. In years when Alto pumpers must resolve a make-up obligation to Centro pumpers, these transactions represent a substantial amount of total trading (and easily exceed intra-Centro trading). With the exception of the market's very early years, trading of FPA has reliably exceeded 20,000 acre-feet per year, which equals 15-20 percent of average annual pumping.

FIGURE C2

Volume transacted on spot market has exceeded 20,000 acre-feet since the 1990s



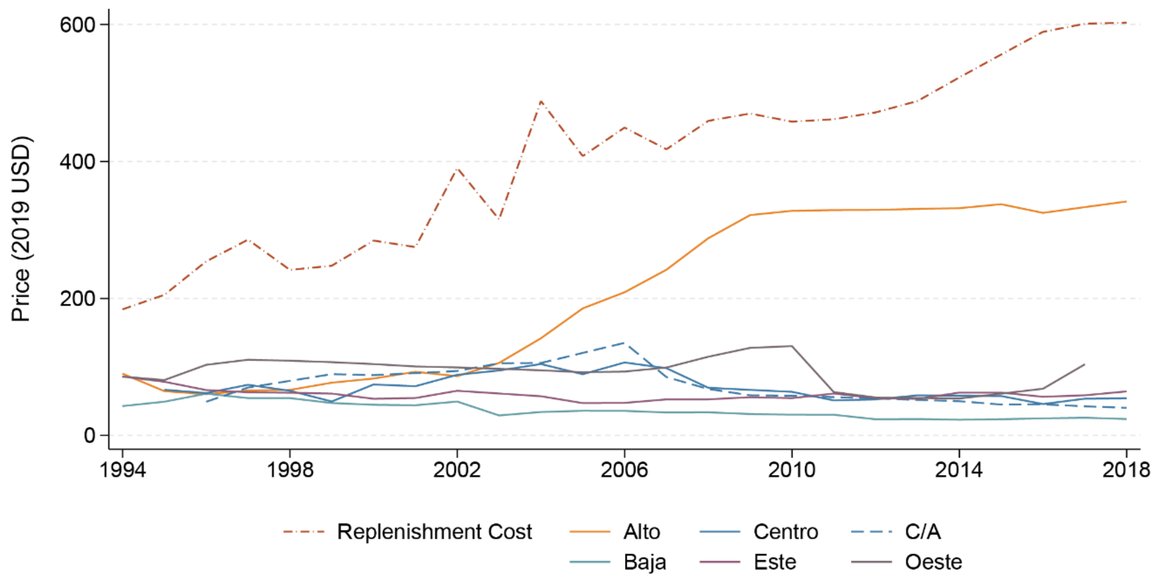
SOURCE: Author calculations using data from Mojave Watermaster.

NOTE: Lease volumes across Mojave's five subareas. Both current-year FPA and carryover allowances included in calculation. "C/A" represents "make-up water" market between Alto buyers and Cento sellers. All values in acre-feet.

In general, the price of water is bounded by the replenishment cost. The watermaster levies this charge on pumpers who exceed their allotment. Increases in the rate of ramp-down in the early 2000s contributed to increasing allocations prices, especially in Alto, where particularly high-value water users found a regular need to make up allowance shortfalls on the market. Price declines in Centro and Oeste in the late 2000s reflect increased efficiency on the part of municipal providers and significant acquisitions of permanent rights on the part of large water users (obviating the need for spot market purchases), respectively.

FIGURE C3

Spot market prices have risen in some subareas and fallen in others



SOURCE: Author calculations using data from Mojave Watermaster.

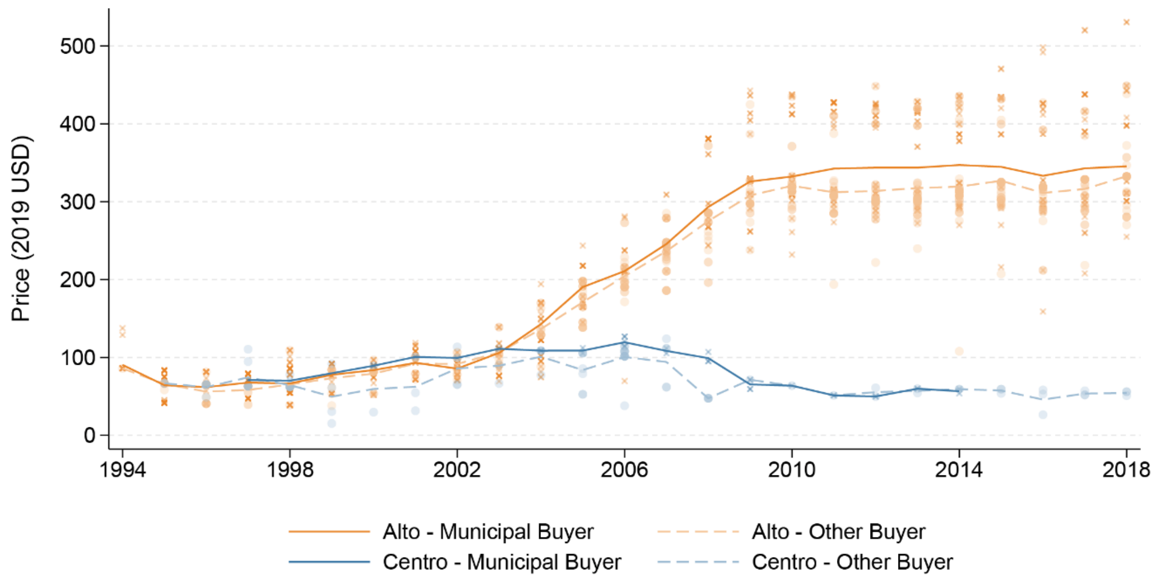
NOTE: Mean annual lease prices for pumping allowances across Mojave's five subareas. Replenishment water cost provided for reference. Both current-year FPA and carryover allowances included in calculation. "C/A" represents "make-up water" market between Alto buyers and Cento sellers. All values are per acre-foot and in 2019 USD.

Across all subareas, almost half of all FPA transfers involve a municipal buyer. In the other half of transactions, buyers include agriculture, especially in subareas where municipal demands are limited; recreational lake operators, which are common in the Mojave; various industrial operations, including mining and cement production; and, in recent years, environmental interests. Transactions in which a municipal supplier sells to another municipality are rare, and those in which water leaves municipal use for another sector are practically nonexistent.

The role that municipal water users play in affecting the market price is reflected in Figure C4. In Centro, municipal water use reductions have led to the exit of suppliers from the purchasing market—and precipitated a decline in price.[1] Prices paid by municipal users historically had exceeded those paid by others, but, beginning in 2009, the slow exit of municipal users coincides with an approximate halving of the market price from around $100 per acre-foot to $50. In Alto, no such reduction has occurred, and indeed a wedge between the average price paid for water between urban and other users has emerged over time. Price discrimination on the part of brokers may be one explanation.

[1] For example, the utility serving Barstow pumped approximately 8,500 acre-feet in 2005, but total water pumped had declined to approximately 5,000 acre-feet by 2015. During this time, the utility began leasing FPA on the market.

FIGURE C4
Urban purchasers sometimes drive higher prices



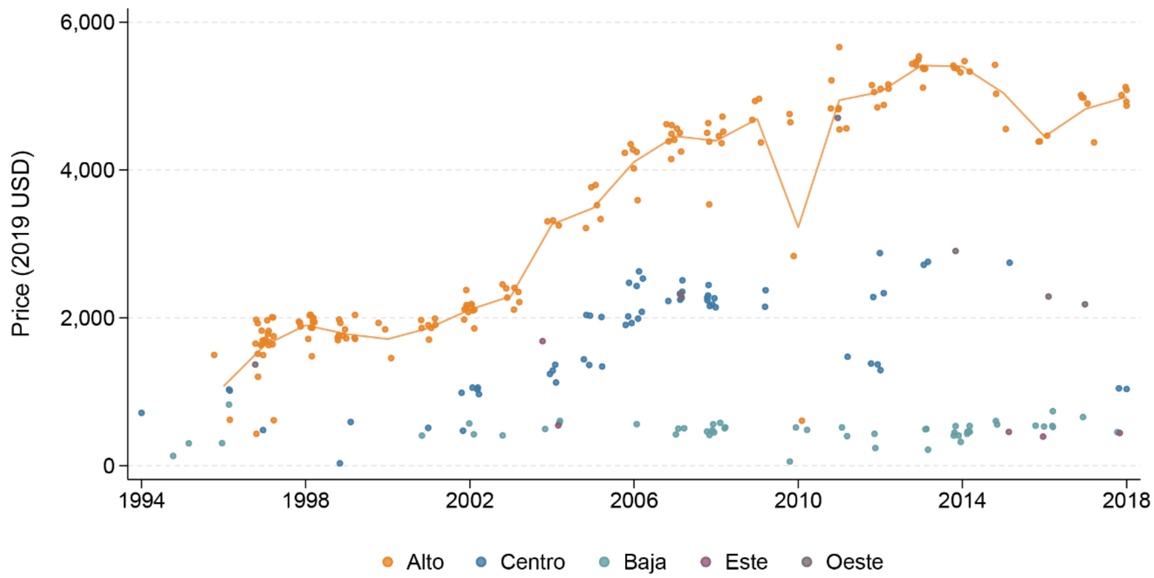
SOURCE: Author calculations using data from Mojave Watermaster.

NOTE: Transactions marked with "x" designate urban buyers, while circles reflect other purchasers. Solid lines track prices paid by municipal users, and dashed lines track prices paid by others. All values are per acre-foot and in 2019 USD.

Market participants also trade permanent BAP entitlements, albeit less frequently than FPA or carryover entitlements. While thousands of FPA transfers have been undertaken since adjudication, slightly under 600 arm's-length BAP transfers were recorded through the 2018-19 water year. Figure C5 plots the per-acre-foot price of every arm's-length transaction over the 24 years for which data are available. The price of BAP entitlements capitalizes the value of being able to pump for many years and therefore exceeds the price of an acre-foot of FPA allowance by typically more than an order of magnitude. In total, arm's-length transactions have resulted in over 170,000 acre-feet of face-value BAP changing hands.[2]

[2] Because BAP entitles a user to pump for many years, it can be useful to translate face-value volumes into "committed water" using a standard perpetuity calculation. Using a 5% discount rate, arm's-length BAP transactions have committed over 3.5 million acre-feet of water to transfer to date.

FIGURE C5
Sale prices have risen the most in the Alto subarea



SOURCE: Author calculations using data from Mojave Watermaster.

NOTE: Permanent sale prices for production allowances across Mojave's five subareas. Each dot represents one arm's-length sale, and individual observations are binned by year but jittered to reduce overlap. Line follows the mean of Alto sales, the subarea with most consistent sales activity. All prices are per acre-foot of BAP and in 2019 USD.

The adjudication was motivated in large part by a need to safeguard future access for cities; today, municipal service providers play a large role in the long-term transfer market in areas with growing urban centers. In the Alto subarea, 47 percent of long-term trades have moved water into urban uses (50 percent of transferred water rights by volume). In contrast, the primarily agricultural Baja subarea has only seen 1 percent of permanently transferred water go to drinking water uses. Other prominent buyers of BAP include recreational lake organizations and solar power generation firms.

Market Solutions for Local Management Issues

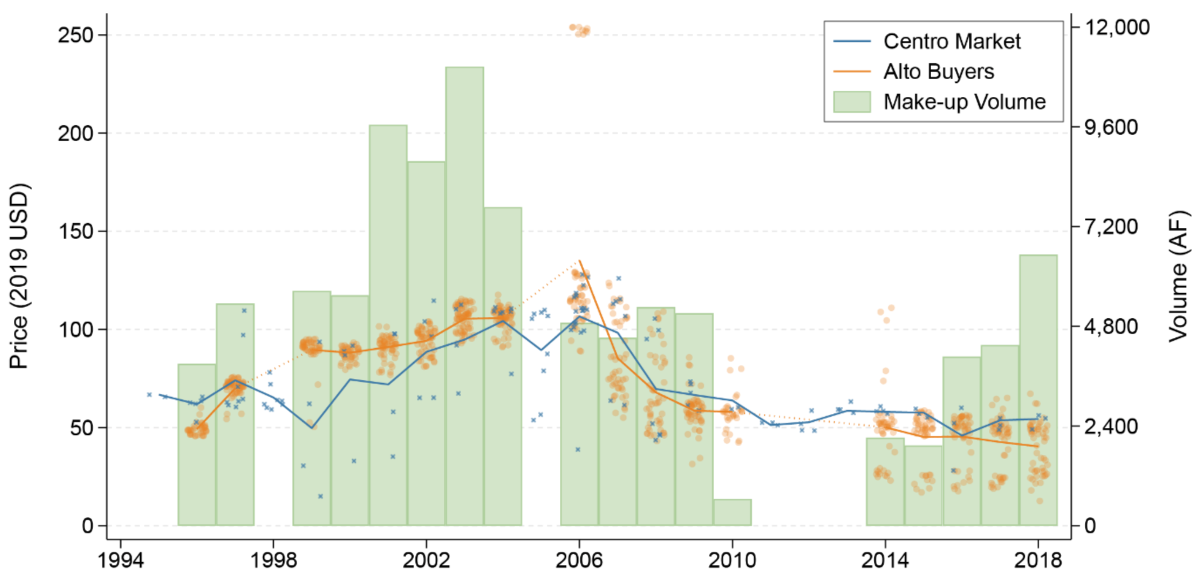
The market for groundwater in the Mojave has provided an opportunity to resolve some disputes about water allocation and management that otherwise may have proved difficult to address through political or other means. Exchanges to make up for insufficient water delivery to downstream subareas are one such example.

Although the Mojave adjudication delineated hydrologically distinct subareas, pumping in one subarea can influence the amount of water that enters another. Therefore, the adjudication defined flow requirements between subareas. For example, Alto must deliver a certain amount of water to the downstream Centro subarea, and the watermaster estimates the relevant flows each year. When estimated annual flow falls below this level, all pumpers in the Alto subarea incur a one-time "make-up" obligation to offset this deficit. Each pumper's proportional obligation is equal to his or her share of pumping within the cap for the year in which flow to Centro was insufficient. Although purchasing imported replenishment water from the watermaster is an option to address the shortfall, this obligation is typically offset by acquiring pumping rights from pumpers in Centro and retiring them (at a 2:1 rate).

This system resolves the dispute over downstream deliveries, but it also provides upstream pumpers in Alto with flexibility. Figure C6 depicts the lease market for pumping allowances in Centro. Allowances may be transacted within the Centro market or sold to buyers in Alto. For the most part, the price for leases purchased by buyers in Alto tracks that of intra-Centro leases. The option to lease to Alto buyers can provide an important outlet for Centro users to monetize their rights: Alto buyers accounted for over 80 percent of Centro sales by volume in 15 of the 18 years with positive makeup obligations. Overall, this market-based system allows (a) Alto users to offset the physical impacts of insufficient deliveries, (b) some Centro users to monetize pumping rights, and (c) Alto users to avoid undertaking costly cutbacks or purchasing expensive replenishment water. Had Alto users instead bought replenishment water to offset the volumes depicted in Figure 2, they would have incurred approximately $15 million in additional costs.

FIGURE C6

Make-up obligations drive activity in the Centro groundwater market



SOURCE: Author calculations using data from Mojave Watermaster.

NOTE: Each dot represents one arm's-length sale, and individual observations are organized by year but jittered to reduce overlap. Lines follow mean of sales within Centro and to buyers in Alto. All prices are per acre-foot and in 2019 USD, and volumes are in acre-feet.

Introducing new buyers to the market may affect prices, and this relationship between make-up obligation volumes and the market price that Centro sellers face can be quantified. Table C1 presents coefficient estimates from naïve least squares as well as two-stage least squares regressions of the market price for Centro pumping permits on several variable sets. Column (3), the preferred specification, documents a highly elastic supply: historically, a 1,000 acre-foot increase in transaction volume was associated with an increase of just $3.37 in the permit price. Centro pumpers may benefit from the market linkage by enjoying an outlet to monetize rights, but asset values only increase substantially in years with especially large make-up obligations.

TABLE C1
Effect of make-up purchase obligations on Centro permit price

	Effect on Market Price (2019 USD)		
	(1)	(2)	(3)
Volume of Make-up Purchased	3.55***		
	(0.91)		
Market Volume (Instrumented)		4.08***	3.37***
		(1.05)	(0.86)
Year Trend			-1.45***
			(0.43)
Observations	24	24	24

SOURCES: Author estimates using data from Mojave Watermaster.

NOTES: Coefficients for regressions of the market price of Centro annual pumping permits on the volume of make-up water purchased (in KAF) (column (1)), the total volume of market transactions, instrumented by make-up volume purchased using two-stage least squares regression (column (2)), and the instrumented volume, including a year-trend variable (column (3)). Make-up water purchased rarely deviates from the full make-up obligation, which is determined largely by lagged precipitation and estimated subterranean flows, rendering make-up volume a plausibly exogenous demand shifter. Robust standard errors in parentheses and statistical significance starred: * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Participants have also leveraged markets to reduce groundwater drawdown as well as provide other public goods. For instance, the Mojave Water Agency (MWA) purchased some rights to address lingering overdraft. Although the ramp-down of rights was defined for the first five years of adjudication by the court judgement, additional ramp-down beyond that must be proposed by the watermaster and approved by the court. In some years, the court chose not to approve recommendations from the watermaster to lower FPA allocations in the Baja subarea, and at one point even adopted a moratorium on ramp-down. As a result, Baja remained in a state of overdraft for many years. In 2019, the MWA purchased approximately 7,200 acre-feet of BAP in order to conserve groundwater and thereby bring the basin closer to long-term balance. Where other approaches to address overdraft (i.e., a continuation of across-the-board ramp-downs) proved difficult to implement, a market solution that compensated parties for foregone benefits succeeded.

In other cases, environmental interests have acquired pumping rights for various purposes. The California Department of Fish & Wildlife (CDFW) has been a regular participant in Alto's FPA market in recent years for its Mojave Narrows Regional Park, and in 2001 it purchased over 900 acre-feet of BAP in Baja for its Camp Cady Wildlife Area. CDFW uses these water rights to irrigate some riparian habitat at Camp Cady. In 2019, the Department stated that it has continuing plans to purchase additional BAP rights throughout the Mojave Basin and retire them (Ellsworth, 2019). Private organizations have also taken part in the market, with BAP purchases by the Western Rivers Conservancy and the Mojave Desert Land Trust in 2015 and 2018, respectively. Such acquisitions often occur alongside land transactions, and the associated water rights can be sold, managed as an asset for financial return, or used directly to provide environmental benefit. While some of the purchases mentioned above were funded by tax dollars, alternative arrangements involving funding from environmental groups and other private parties are clearly also possible.

REFERENCE

Ayres, A., K. C. Meng, and A. J. Plantinga. 2021. "Do Environmental Markets Improve on Open Access? Evidence from California Groundwater Rights." *Journal of Political Economy, 129(10)*.

Ellsworth, A. 2019. Declaration of Alisa Ellsworth in Support of the Department of Fish and Wildlife's Response to Watermaster's Motion to Adjust Free Production Allowance for the 2019-20 Water Year. Superior Court of the State of California for the County of Riverside. June 6.

Nature-based Solutions on the Humboldt River

PRESENTED BY

Maddie Barrie

The Nature Conservancy - Nevada

Source: © The Nature Conservancy in Nevada

The Nature Conservancy Nevada

Definition of Nature-based Solutions

Nature-based solutions (NBS) is the sustainable management and use of natural features and processes to tackle socio-environmental issues. NBS may use nature and natural systems to help address conjunctive management issue and water security.

On the Humboldt River, NBS utilized to benefit conjunctive management through:

1. Managed Aquifer Recharge (MAR)
2. Restoration

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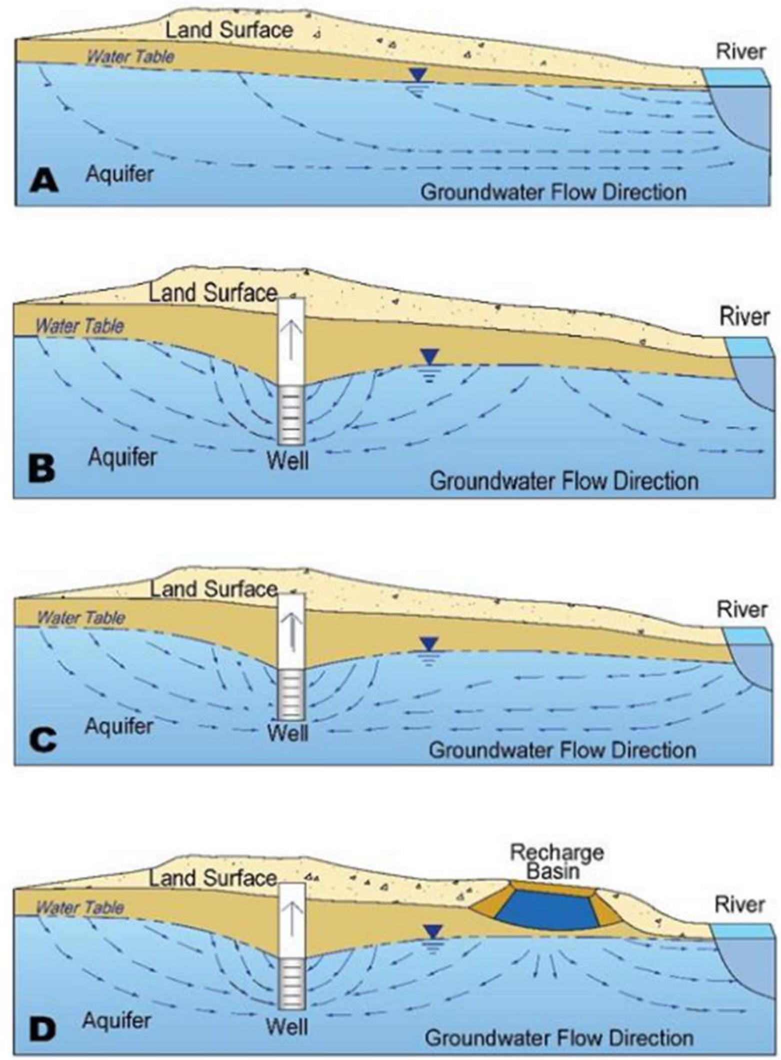
Managed Aquifer Recharge (MAR)

- Replenish aquifer which increases water quantity in river
- No withdrawal, focused on replenishing surface water
- Recharging water underground in key areas can stabilize or increase groundwater levels and restore streamflow
- Ecosystem benefit to wetlands and springs



Source: Cochise Conservation and Recharge Network

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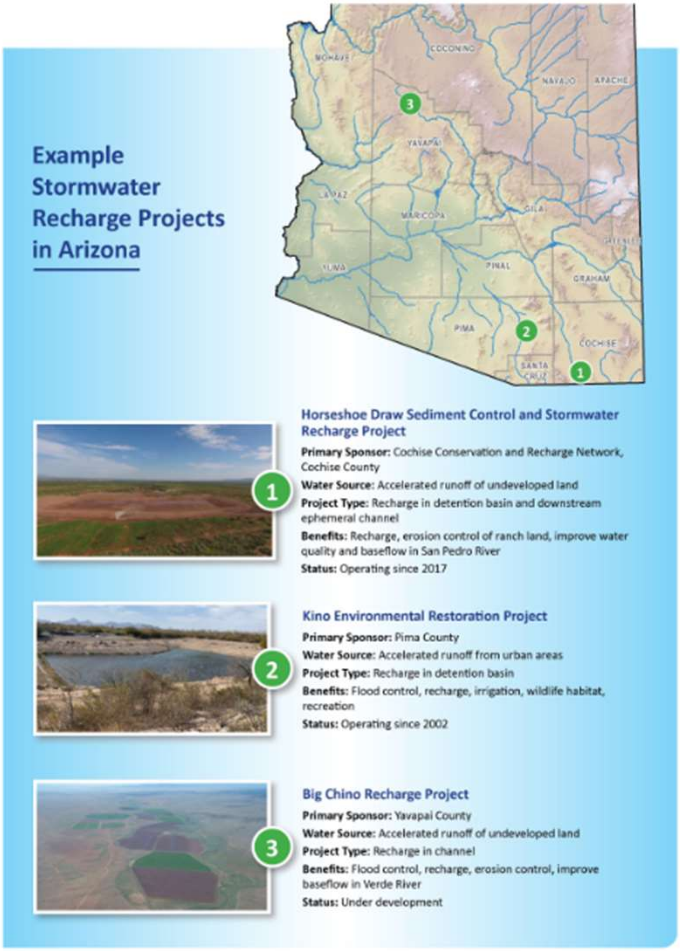

Source: Montgomery and Associates

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TNC Arizona – Flood MAR

- TNC Arizona founding member of Cochise Conservation & Recharge Network (CCRN)
- 3 active recharge sites along the San Pedro River
- 8+ acre detention basins, constructed channels, recharge cells, dry wells and infiltration trenches
- Total Benefits 47,404 acre-feet (AF) of recharged pumping
  - 2015-2022

CCRN PROJECT SITES

The map at right shows the extent of the SPRNCA shaded in gray. Numbers 1-14 on the map correspond with riparian health assessment reaches. The green numbers and shapes alongside the map represent the current CCRN project sites, and the blue numbers and shapes show future projects.

1 Babocomari Floodplain Protection Site

This 105-acre site precludes future pumping through conservation easements. Located along the Babocomari River, the largest tributary to the Upper San Pedro, the project protects the natural floodplain. Flood flows during summer monsoons increase groundwater levels that support riparian vegetation and stream flows.

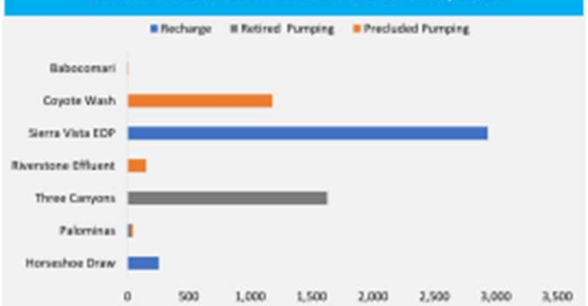
2 Coyote Wash Stormwater Management Project (future)

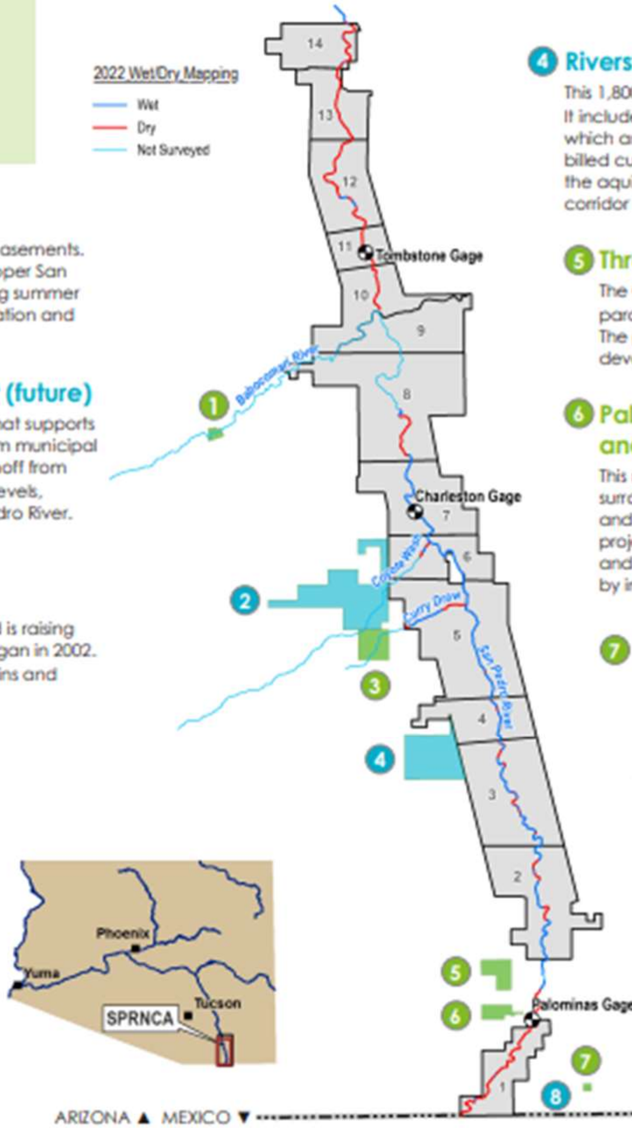
This 3,000-acre parcel precludes future pumping in a critical area that supports river baseflows and creates a buffer zone that protects the river from municipal groundwater pumping centers. The project will direct urbanized runoff from Sierra Vista in an ephemeral stream channel to raise groundwater levels, reduce runoff and erosion, and protect water quality in the San Pedro River.

3 City of Sierra Vista Effluent Recharge at the Environmental Operations Park

This project recharges the city's Class A-quality treated effluent and is raising groundwater levels in a critical area. Operation and monitoring began in 2002. Approximately 2,700 AF/yr is recharged between the recharge basins and constructed wetlands.

Annual Water Benefits in Acre-Feet, 2022





4 Riverstone Effluent Project (future)

This 1,800-acre parcel precludes future pumping adjacent to the SPRNCA. It includes the ephemeral channels of Ramsey and Carr washes, portions of which are designated as critical habitat for the threatened western yellow-billed cuckoo. Effluent from the City of Sierra Vista will be used to replenish the aquifer and restore degraded critical habitat connected to the riparian corridor of the San Pedro River.

5 Three Canyons Conservation Site

The City of Sierra Vista holds a conservation easement on this 480-acre parcel, which has been retired from high-volume irrigation pumping. The project permanently limited future groundwater pumping and development.

6 Palominas Stormwater Recharge and Flood Control Project

This multi-benefit project conveys natural sheetflow runoff from surrounding areas into a large detention basin, mitigating flooding and enhancing recharge in a constructed downstream channel. The project's 13 recharge cells and enhancement structures (6 dry wells and 3 infiltration trenches) reduce the evaporative losses of stormwater by infiltrating more runoff back into the ground.

7 Horseshoe Draw Sediment Control and Stormwater Recharge Project

Horseshoe Draw is an ephemeral tributary to the Upper San Pedro River. This project receives accelerated runoff that originates in the San Jose Mountains in Mexico. Before the recharge project was constructed, a large head-cut had been steadily eroding Horseshoe Draw upstream of its confluence with the San Pedro River. The project consists of an 8-acre detention basin that collects and slows the runoff, enhances infiltration to the aquifer, and improves downstream water quality.

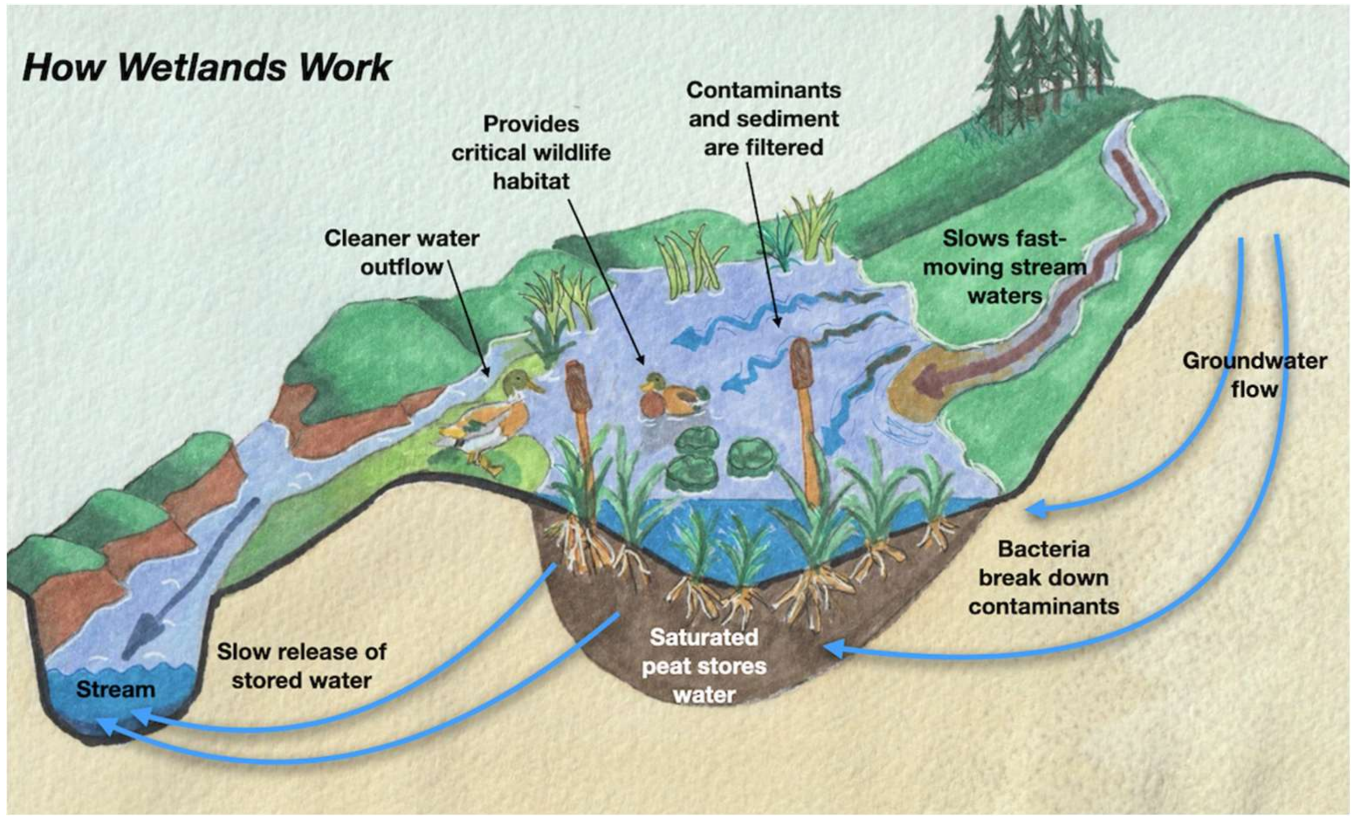
8 Bisbee Effluent Recharge Project (future)

This project will be located between the international border and Highway 92 in Palominas at a location to be determined. Over 20 years of monitoring data show longer reaches of the river are becoming dry in this area during the summer months. The project will recharge a minimum of 200 AF/year of effluent transported via a 13-mile pipeline from the City of Bisbee's San Jose Wastewater Treatment Plant.

Source: Cochise Conservation and Recharge Network

Floodplain wetland and river restoration

- Increase water yield while enhancing natural system
  - Water quality
  - Carbon sequestration
  - Flood control



Source: Adelia Ritchie

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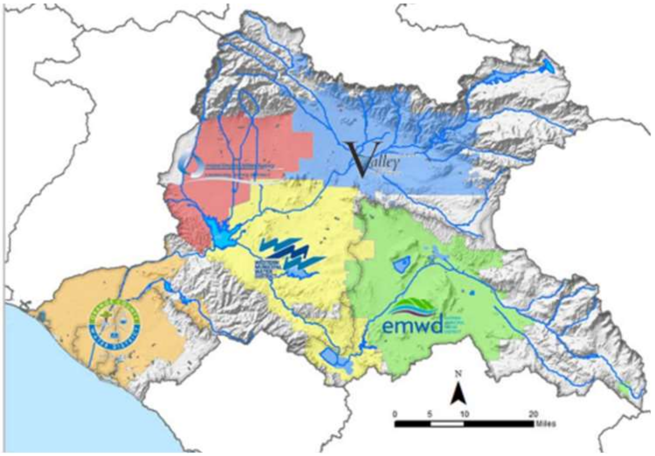

Source: © Inland Empire Utilities Agency

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Restoration examples

The Santa Ana River Conservation and Conjunctive Use Program (SARCCUP)

- Conjunctive Use Program for the watershed
- Invasive weed removal and habitat creation/restoration
- Water use efficiency and water conservation measures
- In 2022 8,120 AF of water were recharged at 18 sites in the watershed

Source: © Simon Williams/The Nature Conservancy in Nevada

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Restoration examples

Truckee River Restoration

- Collaborative effort, TNC piloted restoration efforts at McCarran Ranch Preserve
  - 10 miles of Lower Truckee restored
- Reconnecting the river to its floodplain to reduce channel narrowing
  - Water spread along floodplain allows more recharge of groundwater
- Additional benefits to native vegetation, water quality, and wildlife

Potential Steps and Timeline

- Determine locations for recharge and restoration projects
  - TNC Arizona completed statewide suitability analysis to identify locations for aquifer recharge. Arizona prioritized proximity to gravel pits as potential recharge basins
    - 9 months
    - $60,000
- Find funding
- Design project
- Implement project
- Permitting
- Monitoring before during and after
- Timeline for this process will vary depending on scale
  - CCRN project with pipeline and recharge facility $8M

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Potential Funding Sources

- NRCS EQUIP
- USDA Conservation Innovation grants
- WaterSMART
  - Since January 2021, Reclamation has selected 539 projects to be funded with $239.8 million in WaterSMART funding, in conjunction with $2 billion in non-Federal funding, across the western states.
  - Recharge related funding for planning and implementation
    - Drought resilience projects
    - Planning and design projects
    - Cooperative watershed management projects
  - Restoration related funding for planning and implementation
    - Aquatic ecosystems projects

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Considerations for implementing nature-based solutions

- Variable cost from thousands to millions of dollars
  - Match may be required for federal grants
- Location of restoration efforts and MAR requires study
  - Potential for long timeline to results
  - Focus on restoring river ecosystem
- Conjunctive management solutions should not preclude the ability of water users to apply nature-based solutions

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Expected Outcomes

Improved reliability for Humboldt water supply and benefits to ecosystem

- Restoration of natural river channels and water supply
- Increases to water quality, native vegetation, and wildlife

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Modeling Tool Updates and Uses Related to Allocations of Costs for Management of the River

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Management and Mitigation Programs

Will likely require funding mechanism for a Conservation District or similar entity.

- Management of resources and tracking of future progress
- Updates to modeling and advancement of technical tools
- Improvements in monitoring of water levels, stream flows and river flow loss zones
- Funding of mitigation projects
  - Regional augmentation programs
  - Water right retirement
  - Other

Necessity of Model Updates

Routine audits for accuracy of prediction needed, recommended on a water-year basis.

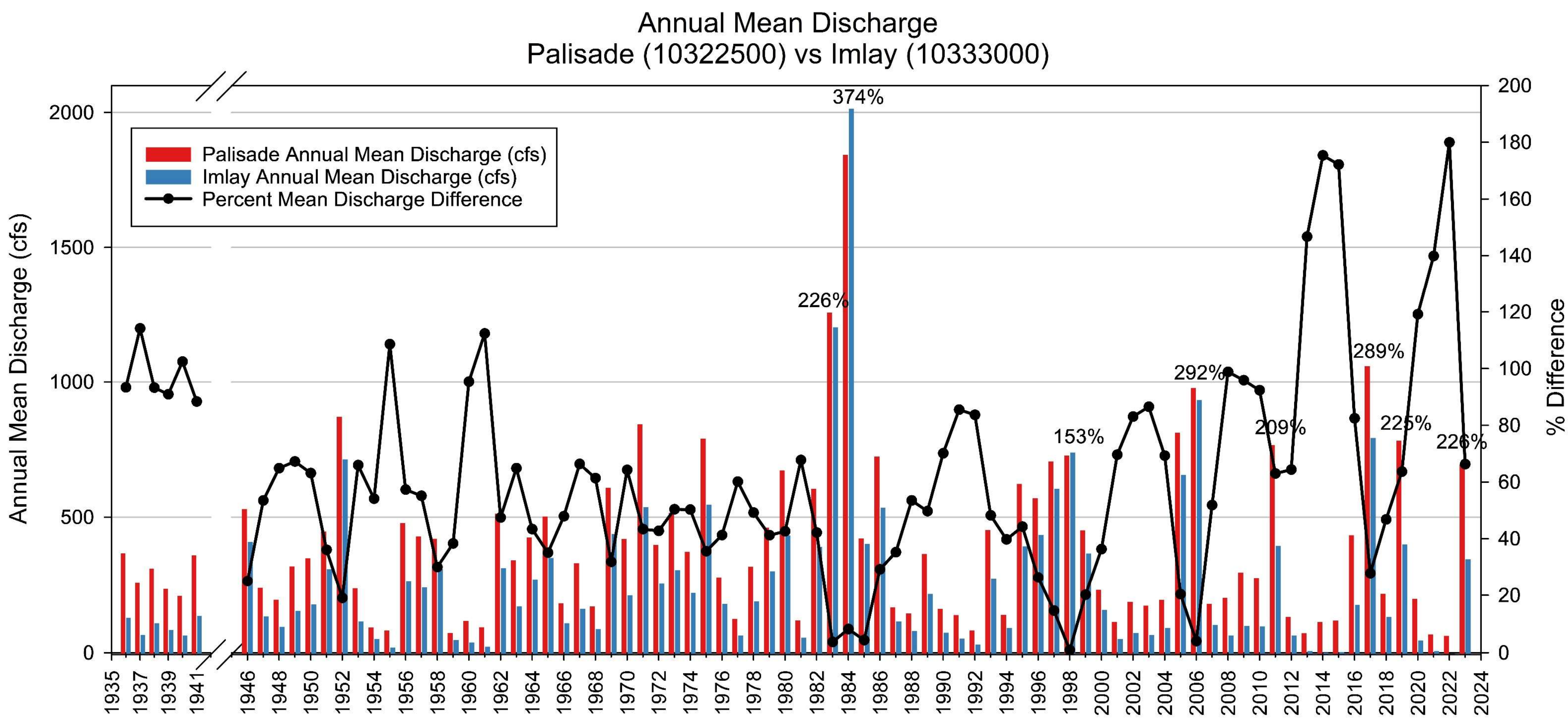
WY2023 was unique and the ability of the models to predict river flow losses is needed (especially for Middle Humboldt model).

If predicted deviates significantly from observed (measured), then model calibration updates should be undertaken to achieve a better simulation fit to observed data.

Updates to models to accommodate desired predictive analysis.

Models built for the purpose of assessing stream flow capture, but other attributes for water resources management may be desired (for example ability to simulate conveyance of augmentation water input to the river, and simulation of South Fork Reservoir)

Humboldt River Flows WY2023 Provisional



Management and Mitigation Cost Allocation Concepts to Consider

Permitted underground water rights

- Allowances for temporarily placing into inactive status while protection of the water right from forfeiture

Active versus inactive water rights

High-capacity water rights or wells vs low capacity / domestic wells

Pumped volumes (prior year?)

Modeled capture percentages

- Long-term average based
- Current conditions based
- Might be variable annually depending on water yield flows and pumping rates

Distance from river or tributary based

Over-appropriated basins

Over-pumped basins

Basin-wide predicted river flow capture based

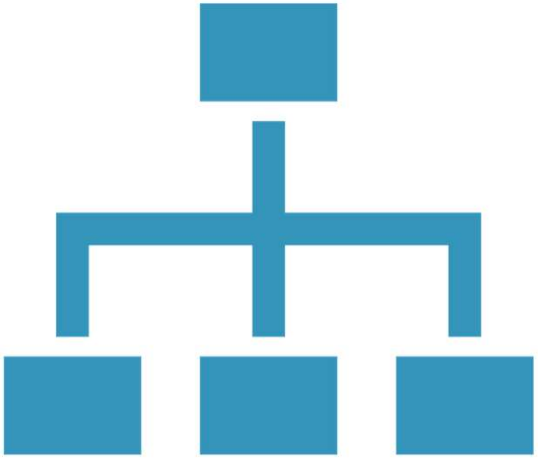
Tiered Assessments Approach

- Tiers of assessments may be desired
- Tier I – management assessment common to all basins
  - Monitoring and reporting activities
- Tier II – applicable to specific basins or capture zones due to higher related costs for management

  A) Over-appropriated / over pumped basins

  B) High capture basins

  C) High capture zones or distances from river



Creating a Funding Mechanism

- Even if an organization exists that can manage a groundwater management program in Nevada (such as a Conservation District), or a new organization formed (most likely by Cooperative Agreement) a funding mechanism for groundwater management in Nevada will need to be authorized by legislature as existing tools are inadequate

- In 2014, California enacted the Sustainable Groundwater Management Act (SGMA) which included new fee mechanisms based on existing law that could be used to fund groundwater management activities

Nothing Happens without Funding

Groundwater Management agencies have a regulatory role, an implementation role and a support role

- **Step 1:** Fund the Regulatory Functions of the Agency
  - Administration (staffing, billing, insurance, legal services, reporting to NDWR etc.)
  - Reserves
- **Step 2:** Fund implementation of the Groundwater Sustainability Plan
  - Investigative studies and programs
  - Joint programs with other agencies and non-profits
  - Water rights buyout
  - Mitigation program
  - Capital projects
- **Step 3:** Support programs by leveraging funding in every way possible (grants, public-private partnerships, hosting data exchange, grant-writing hub for farmers)

SGMA Fee Mechanisms

1. Fee to fund Regulatory Functions only
    - Create a management plan and keep it updated, track well and pumping activity, conduct studies, fill data gaps (install monitoring wells, weather stations etc.), inspect/enforce regulations adopted by the agency, general program administration expenses and maintain a prudent reserve
2. Fee to fund Regulatory and Management Functions
    - In addition to the above, management functions include land acquisition and building projects (examples – recharge basins, surface water delivery pipelines)

SGMA also specified that the agency could charge a customer for meter installation cost recovery

If a GSA is unable to fund itself, the State will step in to manage the area and impose its own fees

Funding Structures Options

- Wellhead Fee
- Parcel Fee
- Acreage Fee
- Point of Connection Fee
- Extraction Fee
- Hybrid – combination of above

- Selection of fee structure depends on local circumstance – is the fee only going to be applicable to irrigators, or will it be charged to all types of users (municipal, industrial, mining)?

- Need to provide parameters for new fee mechanism(s) authorized by legislature – for example in California the fees cannot exceed the amount necessary to cover reasonable costs of the governmental activity and the amount allocated to each payor must bear a reasonable relationship to the payor's burdens on the benefits received

Important Lessons Learned from California

- Takes real grassroots efforts to manage groundwater due to the unique issues and customer base in any one area
- Few regulatory actions and no voluntary actions will occur unless the affected community (usually primarily the farming community) believes in the process and protection of their rights; ***good outreach and communication is critical***
- Senior water right holders need an incentive to participate in water reduction programs as there is no compelling reason for them to do so; ***participation in funding requires demonstration of reasonableness to treat all equitably***
- Conservation value of groundwater management to wildlife, habitats and cultural resources needs greater emphasis and funding: ***tap into non-traditional funding sources as attainable***
- Modifying farming practices to meet groundwater sustainability in some hydrographic basins (switching crops, set-aside rotations, regenerative farming) requires massive financial support: ***a next phase the agency should be considering***

Example Fee Structure:

Salinas Valley Basin GSA

- Tier 1 fee costs allocated 90% to Agriculture and 10% to all other users
- Tier 2 fee costs allocated by historical average pumping in each subbasin

*Properties with domestic wells exempt currently

[1] Includes an allowance for uncollectable revenue and land use change of 2.5% for agriculture and 6.0% for all other users.

Subbasin	Tier 1 Fee	Tier 2 Fee	Total Fee
Eastside		[1]	
Per Irrigated Acre	$9.59	$1.96	$11.55
Per Connection	$4.51	$0.25	$4.76
Langley			
Per Irrigated Acre	$9.59	$10.26	$19.85
Per Connection	$4.51	$1.40	$5.91
Forebay			
Per Irrigated Acre	$9.59	$2.66	$12.25
Per Connection	$4.51	$2.27	$6.78
Monterey			
Per Irrigated Acre	$9.59	$42.01	$51.60
Per Connection	$4.51	$0.91	$5.42
180/400 Foot			
Per Irrigated Acre	$9.59	$4.47	$14.05
Per Connection	$4.51	$1.25	$5.76
Upper Valley			
Per Irrigated Acre	$9.59	$2.52	$12.11
Per Connection	$4.51	$5.49	$10.00

Example Fee Structure:

Merced Irrigation Urban GSA

- Costs split between Agriculture (78%) and Urban (22%) based on estimated pumping

*All properties, including those with a domestic well are charged

Fee for Fiscal Year 2023-24	Fee Category	Merced County Assessor Land Use Codes
Agricultural (per Acre)		
$6.48	All Agricultural	0701 0702 0703 0704 0706 0707 0708 0711 0801 0802 0804 0806 0807 0808 0813 0814 0909 0911 1207 1208 1313 1408 1414
Urban Residential (per Acre)		
$6.86	Mobile Home	1702 1703 1704 1717
$7.12	Single Family Detached	0101 0102 0103 0104 0105 0106 0117 0125
$9.12	Single Family >0.9 acre lot	same codes as for Single Family Detached
$11.30	Single Family Attached	0130 0201 0202 0203 0204 1202 1203
$16.84	Apartments	0301 0302 0303 0304
Urban Non-Residential (per Acre)		
$9.44	Commercial	0402 0403 0404 0405 0406 0407 0408 0430
$9.72	Industrial	0601 0603 0604 0606
$6.46	Religious	1020 2020
$8.30	Government	1515 1919
$1.28	Railroad/Utilities	1616
$4.56	Open Space	1818 2121 3030
$0.74	Vacant	1001 1002 1003 1004 1005 1006 1012 1030

Creating a Funding Mechanism

- Based on legal foundation
- Directed by Board of the Agency managing the program
- Funding structure will be based on a combination of scientific knowledge and policy objectives
    - Requires technical expertise (hydrologist, engineer, water rights specialist, GIS technician)
    - Outreach coordinator
    - Fee consultant (puts together the technical expertise with the funding requirement and the desires of the customer base)

Conservation of Water Through Better Management on the Humboldt River - Utilizing Tighter Deliveries On Priority and Hiring More Personnel to Administer Water Deliveries Water

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Addressing both surface water and groundwater individually, as well as conjunctively, can help lead to a more sustainable and reliable water system. To help surface water shortages on the Humboldt River and it's tributaries, tighter and better management of the system can be implemented.

From years of watching the management of the Humboldt River, Pershing County Water Conservation District has noticed several areas where the system can be better managed. These include:

- River Commissioners serving the same priority below Palisade as above Palisade
- River Commissioners not raising priority of water service until all of the current priority deliveries are served.
- Requiring that all water deliveries be made by Ditch Riders and River Commissioners (individual water users should not be allowed to operate their own delivery gates).
- Providing transparency by creating a real-time database for all surface water delivery records on the Humboldt River and its' tributaries available to the public.
- Creating a publicly available database for all stream measurement stations for flow and elevation and thereby limiting the "measurement & shift" issues that creates issues for stream gauge tracking.
- Re-installing a river gauge at Rose Creek in the Winnemucca area. The largest loss of river water is the Winnemucca segment. A gauge at Rose Creek would assist in monitoring and tracking river loss between Comus and Winnemucca.

PCWCD believes that for long-term success, a funding source should be created to assist in offsetting the costs of management akin to the Federal Water Master on the Truckee or Walker system. These recommendations, if implemented, would vastly improve management on Humboldt River and its' tributaries.

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July 13, 2023

Via Email

Mr. Levi Kryder (lkryder@water.nv.gov)
Department of Conservation and Natural Resources
Division of Water Resources
901 S. Stewart Street. Suite 2002
Carson City, Nevada 89701-5250

Re: Nevada Gold Mines LLC Conjunctive Management Abstract: Future Water Management in the Humboldt River Region

Dear Mr. Kryder:

Nevada Gold Mines LLC is hereby submitting a 1-page abstract in response to the notice received on June 30, 2023, for the Humboldt Conjunctive Management Stakeholder Meeting and Call for Abstracts.

If you have any questions or require any additional information, please contact me by phone at 775-748-1225 or by email at egallegos@nevadagoldmines.com

Sincerely,

Erica Gallegos
Water Resources Engineer
Nevada Gold Mines

Enclosure: Nevada Gold Mines LLC Conjunctive Management Abstract: Future Water Management in the Humboldt River Region

Nevada Gold Mines LLC Conjunctive Management Abstract: Future Water Management in the Humboldt River Region

The term “conjunctive management” can describe a variety of water management tools, and the term continues to evolve as western states amend and update their water laws to address scientific evidence of hydrologically connected surface water and groundwater sources, water shortages, over-appropriation, and the uncertain impacts of climate change. However, implementing conjunctive management principles in a state like Nevada – where groundwater rights and surface water rights have been administered separately for over a century – would be disruptive, unless the transition plan is carefully considered. A successful conjunctive management system rests on both sound policy and economic determinations, as well as sound science that can determine hydrologic connections between surface and groundwater resources with reasonable accuracy. Conjunctive management tools work best where the underlying science is accessible to users and consensus exists on the means, methods, and results. The ultimate goal is to allocate scarce water among users as efficiently and equitably as possible, while recognizing existing vested and decreed property rights.

To effectively develop the framework for conjunctive management, it will be critical for the State Engineer to model capture in the Humboldt River Region and to make the model available for water right holders in the Humboldt River Region to review. Furthermore, the USGS/DRI model has exceeded the schedule, which raises the question of sustainability in maintaining this system and incorporating the best available science in the future. The State Engineer should also consider that a mitigation plan based on a model is not as accurate as a plan based on observed impacts because a model requires several assumptions and has inherent limitations which will result in a real burden to permit applicants.

Other states have implemented conjunctive management with varying degrees of success. But in most cases, those states have spent years studying and understanding the complexity of their hydrologic resources and then designing their state systems to include transition tools to meet the needs of both surface and groundwater water users. Nevada should carefully assess the successes and failures of other states so that it can better understand how to make a successful transition through policy determinations suited for Nevada’s unique economy and hydrological systems.

Other considerations that may aide in managing and developing the framework for conjunctive management include mitigation, voluntary agreements, federally funded voluntary programs, aquifer recharge/recovery storage, water banking, and integrated planning.

Nevada Gold Mines recognizes that in some instances there is a connection between groundwater and surface water and honors the Prior Appropriation Doctrine. However, we also recognize that not all groundwater rights impact surface water rights, so curtailment based solely on priority date will not cure all impacts to surface water and could devastate the State’s economy. Nevada Gold Mines suggests that the State Engineer consider a study to include engaging experts, including those from other jurisdictions, to understand the successes and failures in implementation of various conjunctive management approaches.

ABSTRACT SUBMISSION
August 1, 2023 Humboldt Conjunctive Management Stakeholder Meeting

Conjunctive Use Concept: Groundwater Pumping from Distant Locations for Annual or Targeted Irrigation-Season Flow Augmentation in the Humboldt River

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A potential conjunctive-use water management strategy is proposed for Humboldt River Region based on a framework for augmenting river flows by delivery of pumped groundwater from distal locations to the river. This general type of augmentation strategy has been used in Colorado for decades and has technical merit for consideration. Because of the hydrogeologic variability, this strategy would require site-specific considerations in Nevada and the Humboldt River Region. As a concept, the distal groundwater pumping would have a long-term capture effect on the river, but the percentage and volume of capture would be comparatively small and attenuated in contrast to the instantaneous wet-water delivery benefit to the river. In effect, the incidental capture associated with the augmentation groundwater pumping could be viewed as paying interest on short-term loans. The benefit to be gained from this conjunctive use strategy is that flows in the river would be augmented during more critically dry water-years, and/or seasonally during moderate flow periods to augment decreed water rights for down-stream irrigation. The concept would have the following main requirements:

A. Potential augmentation source areas would need to be defined and would ideally have long-term stream flow capture estimated to be below a certain threshold, for example 10% of the pumped volume after 50 years of continuous pumping. Augmentation source areas could include: 1.) mines where dewatering in excess of mining and milling water uses are occurring, 2.) existing agricultural areas that are distal from the river where willing owners may be willing to convert wholly or partially to the river augmentation water supply, or 3.) at undeveloped locations within basins, that receive substantial recharge and are situated near large areas of phreatophytes with low environmental sensitivity (areas with uncaptured groundwater discharge).
B. Wells and water conveyance infrastructure would need to be permitted, funded, and constructed to deliver water directly to the Humboldt River or a tributary.
C. Operation of the augmentation program water would need to be managed to deliver water to the river at the appropriate times. Augmentation water would be delivered during the decree irrigation season, and during targeted river flow conditions.

The existing USGS / DRI numerical flow models for the Humboldt River Region could be used in a Decision Support System for review, design, permitting, implementation and operation of the augmentation water projects. This concept requires a source of funding for implementation and operation that could potentially be derived from a new duty or use fee spread amongst all permitted groundwater users in the Humboldt River basins, potentially weighted by percent capture of pumping or based on permitted water rights available to pump.

Abstract jointly submitted by PCWCD and Flying M Ranch.

ABSTRACT SUBMISSION

August 1, 2023 Humboldt Conjunctive Management Stakeholder Meeting

Funding Sources for Water Master, River Management, and Gauging

Schroeder Law Offices, P.C.

Caitlin R. Skulan

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This presentation would discuss potential funding schemes and sources for the Humboldt River Water Master, river management, and installation/maintenance of gauges on the river. The presentation would review the schemes, sources, and budgets used elsewhere in Nevada, namely on the Walker River and Truckee Rivers. An example of the type of information that would be discussed is outlined below related to the Walker River. A presentation would focus on how these surface water schemes could be modified and used in the Humboldt Basin.

Walker River

To aid in management and funding for the Walker River, the United States Board of Water Commissioners ("Board" or "Commissioners") and Chief Deputy Water Commissioner/Water Master ("Water Master") for the Walker River submit an annual Report and *Petition for Approval of Budget and Approval of Rate of Assessment* outlining the management activities, precipitation, prior year deliveries, and financial needs for management of the river. Prior to submission of this document to the Decree Court, the Board meets to discuss and consider its budget and rate assessment for the following year and the Water Master presents a proposed budget and rate assessment. Such proposal is considered and deliberated before being voted on by the Commissioners.

The approved July 1, 2023 to June 30, 2024 assessment for the Walker River is three dollars and Fifty Centers ($3.50) for each assessed acre. Assessments are collected by the United States Board of Water Commissioners as well as the Walker River Irrigation District. The projected total operating revenue resulting from these assessments for the 2023-2024 irrigation season based on this assessment is $462,812.00. This revenue will be used to cover various Walker River operating expenses, including salaries and benefits for the Water Master, Staff, and River Riders; $145,000 in gauging expenses; a legal services budget; and various smaller expenses to operate an office and equipment required for Walker River management.

Daily management funded by these assessments are governed by a set of standard operating procedures. Management is facilitated by the Water Master and five (5) river riders. The Water Master meets daily with the local River Riders and ditch riders from the Walker River Irrigation District prior to 11 AM and communicates with the River Riders not locally located by electronic means. At these daily meetings, the next days water deliveries are determined and communicated to the river riders and ditch riders who control the diversion of water from the river system and various ditches. Delivery determinations are based on priority and real time gauging data.

ABSTRACT SUBMISSION
August 1, 2023 Humboldt Conjunctive Management Stakeholder Meeting

Updated Conjunctive Management "White Paper" Submission

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In August 2014, Schroeder Law Offices and the Pershing County Water Conservation District ("PCWCD") authored and provided to the NDWR a "White Paper" surveying how other prior appropriation states were then implementing conjunctive management. This paper was entitled "*Water Management in a Prior Appropriation System: Conjunctive Management Solutions to Groundwater Withdrawals Effecting Surface Water Flows within the Humboldt River Basin.*" The State systems addressed in the White Paper included those in Colorado, Idaho, Utah, Washington, and Oregon.

Schroeder Law Offices is offering to review and update the White Paper and provide current information to the State Engineer in this regard. This may provide insight to other State's conjunctive management schemes, including how they have been implemented and/or updated since the original White Paper's authoring in 2014.

A paper and/or presentation may focus on other states' approaches that may benefit or be of use to Nevada.

HUMBOLDT RIVER ABSTRACT SUBMISSION

Participant: The Nature Conservancy, Nevada

Title: **Nature-based Solutions on the Humboldt River**

a. Brief description of the concept/method/idea and how it would work.

When looking at management decisions along the Humboldt River that will help resolve conjunctive management conflicts in the system, it is important to consider actions that can provide multiple benefits to the system, including positive impacts to ecosystem health in the watershed. Incorporating nature-based solutions that increase water security while also having beneficial environmental impacts could increase water supply resiliency and reliability for the Humboldt River system.

b. Discussion on how to implement this concept and what is needed.

There are several options for nature-based solutions that could be implemented along the Humboldt River to increase water yield and overall ecosystem health. Managed aquifer recharge (MAR) is a nature-based solution that uses the purposeful recharge of water to aquifers for subsequent recovery and environmental benefit. MAR is used by water managers, large pumpers, developers, and others to provide water supply resiliency, helping balance seasonal and periodic decreases in water availability with demands. Floodplain wetland restoration and river restoration can also help increase water yield while enhancing the natural system and increasing water quality for downstream users. The Nature Conservancy's restoration of the lower Truckee River is a good example of such restoration. Consideration of the locations of nature-based solutions that might coincide with returning water to senior water users at the right time, place, and quantity could provide multiple benefits to the Humboldt River system and water users. Such approaches could also provide opportunities for carbon sequestration, improvements in water quality, and flood control.

c. If this concept has been implemented successfully in other states, provide additional information on how it was implemented and examples.

The Nature Conservancy is involved in nearly 50 watershed investment programs that employ nature-based solutions to address a range of challenges, including living with wildfires, mitigating flooding, increasing water quality and dry season availability, and improving market access for farmers and ranchers. The Arizona chapter of The Nature Conservancy has done successful work in flood managed aquifer recharge. Additionally, the Santa Ana River in California has a large-scale conservation and conjunctive-use program designed by the five regional water agencies that uses a combination of a Conjunctive Use Program, invasive weed removal and habitat creation/restoration and water use efficiency and water conservation measures to recharge, store, and increase the dry year yield of the river (see https://www.ieua.org/read-our-reports/santa-ana-river-conservation-and-conjunctive-use-program/).

d. Any pitfalls or issues (funding concept, additional needs by public or State Engineer's office)?

It is important that any conjunctive management regulations or legislation do not preclude the ability of water users to apply nature-based solutions to gain multiple benefits from resolution of conjunctive management issues. In addition, grant funding opportunities may be available to implement approaches that resolve water conflicts while benefitting nature (https://fundingnaturebasedsolutions.nwf.org/). Nature-based solutions will require further studies to identify what area of the watershed would maximize the amount of water being returned to the Humboldt system.

Additional information about nature-based solutions:

Zheng, Y., Ross, A., Villholth, K.G. and Dillon, P. (eds.), 2021. Managing Aquifer Recharge: A Showcase for Resilience and Sustainability. Paris, UNESCO.

ABSTRACT SUBMISSION

August 1, 2023 Humboldt Conjunctive Management Stakeholder Meeting

Modeling Tool Updates and Uses Related to Allocations of Costs for Management of the River

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The modeling tools that were developed by the US Geological Survey (USGS) and Desert Research Institute (DRI) on behalf of the Nevada Division of Water Resources (NDWR) include a stream capture function / tool, whereupon 50-year projected capture can be determined as it relates to future change applications or applications for new appropriations for underground rights. In order to assess historical capture that has occurred by existing underground permits, the modeling tools need additional functionality to enable calculation of present-day capture on a permit level. While it is foreseen that some component of mitigation or augmentation project requirement /funding is needed to deal with present-day stream flow capture, and this model functionality will make equitable allocations possible. Mitigation programs that may require funding include expanded water level and stream gaging data collection, routine audits and updates to the models, and establishment of augmentation and mitigation programs. On the routine model audits, it is notable that WY2023 river flows into Rye Patch are predicted to be notably lower than historically comparable wet year flows, and the ability of the model to accurately simulate WY2023 flow conditions needs to be a priority review item.

The cost allocation structure for river management actions related to groundwater pumping capture of Humboldt River flow could be a tiered approach. There are Groundwater Sustainability Agencies in CA that have adopted this approach for funding of groundwater pumping management actions that are required under SGMA (Salinas Valley GSA example). One tier is a cost per acre irrigated or acre-feet pumped that is uniformly applied to all underground water right users in all hydrologically connected basins, regardless of proximity to the river. The second tier is related to either specific subbasin groundwater management actions required or the degree of long-term declining water levels and severity of groundwater management challenges. In the case of the Humboldt River, the modeled river capture could be the basis of Tier 2. The management cost allocations can therefore be distributed over underground water rights in the 33 hydrographic basins down to and including Lovelock Valley. Research by Interflow Hydrology in 2018 determined that there are approximately 1.9 million acre-feet of underground water rights approved for appropriation by NDWR in these 33 basins. Tier 1 costs may be developed on budgets determined for management expenses relating to all underground water rights in the basins. Tier 2 cost allocations may be an additional cost related to currently projected river capture by volume as determined by the modeling tools (subject to further tool development as noted above), and/or may focus on water rights within a certain distance of the river or a tributary to the river. Interflow Hydrology (2018) estimated the permitted underground water rights within 5 miles of the river or a major tributary to total approximately 1.0 million acre-feet. Based on the magnitude of existing permitted water rights, the management fees that may be imposed may not be overly burdensome, if distributed amongst the duty of underground water right held in an equitable manner.

MEETING: Humboldt Conjunctive Management Workshop

DATE: September 26, 2023

LOCATION: NDWR Tahoe Conference Room

MEETING ATTENDANCE LIST

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MEETING:	**Humboldt Conjunctive Management Workshop**
DATE:	September 26, 2023
LOCATION:	NDWR Tahoe Conference Room

MEETING ATTENDANCE LIST

NAME	ORGANIZATION	PHONE NUMBER
Kip Allander	NDWR	
Sue Braumiller	↓	
Adam Sullivan	↓	
Landon Harris	↓	
Buck	↓	
Malcolm Wilson	↓	
Levi Kryder	↓	
Brian Fitzgerald	↓	

1. Summary

Meeting title	Humboldt stakeholder workshop
Attended participants	41
Start time	9/26/23, 12:38:09 PM
End time	9/26/23, 7:39:37 PM
Meeting duration	7h 1m 28s
Average attendance time	2h 21m 19s

2. Participants

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