Managed Aquifer Recharge as a strategy for Mitigating Drought Impacts on Irrigated Agriculture in California

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Background

- Drought effects on natural water bodies
  - Direct and indirect effects
- Drought responses by humans
  - Not always considering sustainability
- The net effects on nature and humans
  - Pollution, damage to ecosystem, land subsidence and its direct and indirect effects
- California has experienced MAR since 1990th (Arvin-Edison Water Storage District) motivated by uncertainty of water supply to MWD
Change in Groundwater Storage in the Central Valley Aquifer, CA, 1962 – 2014

Definitions

- Managed Aquifer Recharge (MAR):
  - “…the purposeful (intentional) recharge of water to aquifers for subsequent recovery or environmental benefit.” (Dillon et al., 2010).

- Institutions:
  - “comprise norms, regulations and laws that establish the ‘rules of the game’ – that is, that they condition and modify the behavior of individuals and groups so that their actions become more predictable to others.” (Wiggins and Davis, 2006).
MAR potential

106 MAR projects by source of water

Spatio-temporal variability in natural conditions and the resulting heterogeneous groundwater depletion in the Central Valley basins support the hypothesis that MAR could be a promising strategy to mitigate the impacts of future droughts on the Central Valley’s water balance (Scanlon et al. 2012).

Source: Perrone and Merri Rohde (2016)
Research questions and objectives

- Can intentional recharge strengthen resilience to droughts?
  - Is it sustainable, efficient?
  - What role policies and different institutions play in the applicability and efficiency of this strategy?

- We evaluate the performance of MAR
  - Evaluating the Impact of institutions and policies on MAR efficiency
  - Using an integrative model of the Kings Groundwater Basin in the Central Valley of California as our case study.

All models are wrong, but some are still useful

Anonymous
Methodology (1)

- **Regional approach** rather than local approach
- **All water sources** (Surface, GW, Wastewater, Storm water)
- **An iterative process** between a large-scale hydrologic model and the regional economic optimization model (EOM) is used to guarantee that regional decisions within the economic framework are feasible on a wider scale
- **The hydrologic model** was developed using the Water Evaluation and Planning (WEAP) software with a detailed representation of the Kings Groundwater Basin and surrounding area (WEAP/CVPAM—Central Valley Planning Area Modified)
- WEAP/CVPAM simulates the hydrology and water management decisions in the region
  - It includes rainfall-runoff hydrology, water resources infrastructure, water consumption, operating rules, and constraints to the water allocation decisions in the region
- The Economic Optimization Model (EOM) interacts with the results from the Hydrologic model to optimize land use, water applications and level of recharge.
Kings GW Basin-Economic Optimization Framework/Model (EOM)

- Dynamic non-linear deterministic optimization problem
- Represents 30 irrigation subdistricts
- 20-year horizon (SGMA) on an annual time step, calibrated to 2014
- Crop yield production functions that factor water application level and salinity tradeoffs
- Decisions
  - Land allocation across 20 crop categories
  - Water application levels per unit of land
  - Water allocations from each source (surface, groundwater, treated wastewater reuse) to each subdistrict
  - Intentional recharge volume in each subdistrict at each time step
- Explicit simplified representation of groundwater head dynamics (including lateral flows between adjacent subdistricts), and surface flows.
The Region: Kings GW Basin

DAU=Decision Analysis Unit
7 DAUs in our analysis
Kings GW Basin- Data

Land use (main crops) by DAUs

GW sub-basins

Depth to water table

Source: Kings Basin Water Authority
Climate and Policy Scenarios

**Climate**

- **Average**: Annual Average Conditions;
- **Hist1**: Imitates 1975-1996 Climate Conditions (variability);
- **Hist2**: Imitates 1983-2004 Climate Conditions.

**Policy/Institutions**

- **Social Planner (Social)**: Maximization of regional net benefits ignoring income distributions.
- **Sustainable**: Retrieving initial groundwater head at the end of the planning horizon (SGMA).
- **Capacity Sharing (Credit)**: Groundwater extraction is limited by a credit account, which increases with MAR and decreases with pumping. Initial credit endowment is assumed.
### Results (1): Social

Table 7. Annual average land allocation to each crop category as percentage of observed levels by DAU

<table>
<thead>
<tr>
<th></th>
<th>Fallow</th>
<th>Almonds and Pistachios</th>
<th>Field Crops</th>
<th>Fruit</th>
<th>Vegetables</th>
<th>Vine</th>
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<tbody>
<tr>
<td>DAU 233</td>
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<td>99</td>
<td>109</td>
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<tr>
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</tr>
</tbody>
</table>

Figure 21. Average water application level per-acre in each time-step, by DAU.

Figure 28. Time path of VMP of applied water by DAU.

$2.2$ Billion USD
Results (2): Social-Groundwater Dynamics

Figure 25. Time path of groundwater head by DAU (feet above sea level).
Results (3): Policies

- Recharge using excess irrigation increases under the Sustainable scenario.
- Under the Credit scenario, agricultural water use is the lowest, groundwater extraction is the lowest, reuse of treated wastewater is highest.
- Groundwater level increases under Sustainable and Credit more than in the Social scenario, and
- Total recharged quantities are the lowest under Credit.

Figure 30. Panels (a), (c), (e): Time paths of total water use for agriculture, regional groundwater extractions, and treated wastewater reuse in agriculture under the Social, Sustainable, and Credit scenarios, respectively. Panels (b), (d), (f): Time paths of annual recharged quantities by source and groundwater head trend under the Social, Sustainable, and Credit scenarios, respectively.
Results (4): Climate

- Groundwater pumping and treated wastewater reuse are used to stabilize supply

- Land allocated to field crops is fallowed intermittently to offset reductions in surface water supply
Land allocation under the **Credit** scenario

- **Bottom panel:** Land allocation under Average climate conditions

- **Top panel:** Land allocation under Hist1 climate condition

The impact of climate conditions on the scale of land allocation decisions is profound under the **Credit** scenario.

<table>
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<tr>
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<th>Fruit</th>
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<td>101</td>
<td>99</td>
<td>105</td>
<td>99</td>
</tr>
</tbody>
</table>
Measuring the role of climate, policies and institutions

- Recharged quantities decrease with fluctuations in climate
- Value of unit of water recharged generally exceeds the value of water in production

Economic implications of the Credit scenario are detrimental

Differences in climate imply economic cost of $500 million USD under the Credit scenario, and only $2 million USD under the Sustainable scenario

**Table 1. Reductions in Economic Welfare Compared to the Social Scenario (1,000 USD)**

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Hist1</th>
<th>Hist2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social (benchmark)</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Sustainable</td>
<td>7,893</td>
<td>9,921</td>
<td>9,879</td>
</tr>
<tr>
<td>Credit</td>
<td>1,756,849</td>
<td>2,283,592</td>
<td>1,732,795</td>
</tr>
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</table>

Note: The regional economic welfare achieved under the Social scenario is the highest. Therefore, values presented in the table are all negative.

**Table 2. Differences in Total Recharged Quantity and Economic Welfare per Unit of Water Recharged Compared to the Average Climate Simulation Across Policy Scenarios**

<table>
<thead>
<tr>
<th></th>
<th>Differences in Total Quantity Recharged (TAF*)</th>
<th>Differences in Economic Welfare per Unit of Water Recharged ($/AF*)</th>
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<tbody>
<tr>
<td><strong>Hist1</strong></td>
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<tr>
<td>Social</td>
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<tr>
<td>Sustainable</td>
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<td>421</td>
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<tr>
<td>Credit</td>
<td>713</td>
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<tr>
<td><strong>Average</strong></td>
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<td>671</td>
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<td><strong>Hist2</strong></td>
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<tr>
<td>Social</td>
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<td>Sustainable</td>
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<td>294</td>
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<td>Credit</td>
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<td>332</td>
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<tr>
<td><strong>Average</strong></td>
<td>251</td>
<td>436</td>
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</table>

* Note: TAF=thousand acre-feet; AF=acre-feet.
The results show that:

- Total recharged quantities in the region are substantial, ranging between 3.13 MAF to 8.19 MAF, depending on the scenario.
- In most cases, the calculated value of a unit of water recharged is substantial compared to the direct value of water in production (VMP).
- Recharge of treated wastewater, of surface water through excess irrigation of field crops is beneficial for the region, keeping groundwater level in the basin unchanged over time.
- The same recharge strategy is found optimal and even supplemented by intentional recharge through designated infrastructure under the Sustainable scenario—according to the principles of the SGMA legislation.
Discussion (2)

- Under the Credit scenario the region realizes significant land fallowing, replacing permanent crops and inflicting detrimental economic consequences compared to the other policy scenarios.
- This results in economic welfare loss of about $1.75 billion USD annually that is concentrated in DAU 235 (GREEN area).
- The Credit institution incentivizes MAR implementation through intra-basin arrangements, supporting high-value agricultural production in groundwater reliant areas while meeting SGMA objectives.
- There is evidence for such an arrangement (cooperation) between the McMullin Area GSA (which almost completely overlaps DAU 235) and the North Kings GSA (which overlaps DAU 233—PINK area).
Concluding comments

- Intentional recharge through excess irrigation is found to be of value to the region.
- Institutional elements create significant tradeoffs between land use decisions, groundwater exploitation paths and intentional recharge.
- The impact of climate uncertainty depends on the prevailing institutions adopted for groundwater management purposes.
- Cooperation among stakeholders is prefixed as an initial condition assumption.
- High level of heterogeneity in exogenous conditions among stakeholders and their role in maintaining long-term sustainability goals makes the cooperative equilibrium necessary for the success of SGMA, extremely fragile.
Thank you for your interest

- For more technical-detailed information visit the in-line Working Paper at: [https://spp.ucr.edu/sites/g/files/rcwecm1611/files/2020-11/102820_%20Reznik%20et%20al%20MAR%20WP%20Text%20and%20Figures_0.pdf](https://spp.ucr.edu/sites/g/files/rcwecm1611/files/2020-11/102820_%20Reznik%20et%20al%20MAR%20WP%20Text%20and%20Figures_0.pdf)
- For less technical-detailed information visit an article in ARE-UPDATE at: [https://s.giannini.ucop.edu/uploads/pub/2021/04/23/v24n4_2_49OYjqN.pdf](https://s.giannini.ucop.edu/uploads/pub/2021/04/23/v24n4_2_49OYjqN.pdf)
- For questions and/or exchange of ideas please contact me at: adinar@ucr.edu