Variability in Infiltration Rates, Soil Properties, and Changes to Water Quality DuringManaged Aquifer Recharge

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GRA, San Francisco Bay Area Branch
Biltmore Hotel, Santa Clara, CA
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Groundwater recharge: essential for sustaining water resources, a hydrologic research frontier

**Groundwater recharge is:**
- Naturally occurring process
- Primary input to most aquifers
- Most difficult component of hydrologic cycle to measure

**Managed Aquifer Recharge (MAR) is:**
- Increasingly important for groundwater management in CA
- Feasible in many groundwater basins
- Dependent on availability of appropriate supplies
- Method to improve both water *supply* and water *quality*
- A window into cryptic, subsurface processes (natural laboratory)
DWR Water Plan Update 160-98: status and projections for future needs

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<tbody>
<tr>
<td></td>
<td>&quot;normal&quot;</td>
<td>&quot;dry&quot;</td>
<td>&quot;normal&quot;</td>
<td>&quot;dry&quot;</td>
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<tr>
<td>Demand</td>
<td>79.5</td>
<td>64.7</td>
<td>80.1</td>
<td>65.5</td>
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<tr>
<td>Supply</td>
<td>77.9</td>
<td>59.6</td>
<td>79.9</td>
<td>62.8</td>
</tr>
<tr>
<td>(GW)</td>
<td>(12.5)</td>
<td>(15.8)</td>
<td>(12.7)</td>
<td>(16.5)</td>
</tr>
<tr>
<td>Supply – Demand</td>
<td>−1.6</td>
<td>−5.1</td>
<td>−0.2</td>
<td>−2.7</td>
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</tbody>
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All units are Maf

Population (1995): 32.1 M
Population (2020): 47.5 M (+48%) estimated
DWR Water Plan Update 160-05:

<table>
<thead>
<tr>
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<th>2000 &quot;normal&quot;</th>
<th>2001 &quot;dry&quot;</th>
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<tr>
<td>Demand</td>
<td>200.5</td>
<td>159.8</td>
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<tr>
<td>Supply</td>
<td>194.7</td>
<td>145.5</td>
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<tr>
<td>Supply - Demand</td>
<td>–5.8</td>
<td>–14.3</td>
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Now includes environmental uses...

- Climate change mentioned (for first time), not used for projections
- **Draft 2009 Update**: little improvement, e.g., $P_{2005} = 125\%$, $S - D = -4.9$ Maf

All units are **Maf**

*Much of this is overdraft*
Future water “supply” options

Figure 1-1 Range of additional annual water for eight resource management choices

Bulletin 160, 2005
Ground water overdraft can lead to numerous undesirable conditions or processes...

Overdraft can cause:

- seawater intrusion
- subsidence
- permanent loss of storage
- loss of stream or wetland flow
- development of dry gaps
- damage to riparian habitat
- lowering of water quality
**Long-term Global Trends of Nitrogen Release**

- **Year:** 1850 to 2010
- **Reactive nitrogen (teragrams per year):**
  - Natural Fixation
  - Total Anthropogenic
  - Global Population
  - Fertilizer
  - Legume crops
  - Fossil fuel

**Human population (billions):**
- 1850: 1.4
- 1900: 1.6
- 1950: 2.5
- 2000: 6.0
- 2010: 6.1

*Lambert and Driscoll, 2003*
Nitrate concentrations are increasing in many aquifers

Average addition to CA groundwater:
~36 kg N/irrigated acre/ year
Central coastal CA is highly dependent on GW

This provides challenges and opportunities for the Pajaro Valley

GW = 83% of usage

Pajaro River and Pajaro Valley basins

PR basin: 3400 km², multiple counties, tributaries, creeks

PV land use: agricultural, urban, rural

Surface water systems impaired by elevated nutrients and sediment (EPA)

Primary fresh water resource is groundwater

PV GW extraction exceeds the sustainable yield of the basin
Overdraft is a regional challenge

**Pumping:**
~60k ac-ft/yr

**City of Watsonville:**
~7k ac-ft/yr

**Sustainable yield:**
40k–50k (?) ac-ft/yr (depends on pumping distribution, time horizon, natural variability)

**Overdraft:**
10k–20k (?) ac-ft/yr (depends on definition, annual conditions, definitely large)

>50% of basin has groundwater levels below sea level, seawater intrusion at the coast

Map from PVWMA, 2006
Harkins Slough MAR project

- Up to 2000 ac-ft of water may be diverted from Harkins Slough to 7-acre recharge pond, infiltrated into shallow aquifer
- Water later recovered, blended with recycled water and other groundwater, distributed using coastal pipeline
Harkins Slough project uses one kind of managed recharge

• There will be many more Harkins Slough-style projects throughout CA in the next 20+ years.
Research Questions Concerning Managed Aquifer Recharge (MAR)

- How is infiltration distributed spatially and temporally?
- What limits rate(s) of infiltration? Why do changes occur?
- What is the fate of the infiltrated water?
- What is the influence of infiltration and recharge on water quality in underlying aquifer?
- How can MAR help to limit basin nutrient export?
- How can MAR be operated to achieve simultaneous water supply and water quality improvements?
- Can MAR be linked to other efforts, use of low-impact development techniques, storm water retention, etc.?
Sampling and instrumentation

- Soil borings (grain size, carbon)
- Thermal and pressure probes (flow rates, soil properties)
- Piezometers and lysimeters (infiltration-fluid sampling)
- Monitoring wells (water levels, aquifer water sampling)
Quantify whole pond seepage rate through measurements and calculations of mass balance:

\[ S = D + P - E \pm \Delta V \]

\( D = \textit{diversions} \) into pond (60-minute pumping records available from PVWMA SCADA system)

\( P = \textit{precipitation} \) into pond (15-minute precipitation records from gauge installed on site, cross checked with CIMIS)

\( E = \textit{evaporation} \) losses from pond (15-minute values calculated from meterological station installed on site, cross checked with CIMIS)

\( \Delta V = \textit{change in volume of water stored} \) in the pond (15-minute values calculated from pond water levels - pressure gauge - and rating curve relating water level to volume stored.

\( S = \textit{seepage} \) into base of pond, upper limit on recharge rate into underlying aquifer (determined by adding/subtracting other terms)
Seepage rate increases as pond fills, reaches ~0.8–1.0 m/day for four weeks, decreases to ~0.3 m/day for eight weeks, drops to 0.1 m/day.
What is the fate and influence of recharging water?
Recharge:
Arrival of MAR water in the underlying perched aquifer Eolian, fluvial, alluvial sediments

Infiltration:
Passage of water into shallow soils, forms saturated zone, inverted water table
Thermal probes used to determine seepage rates

- Autonomous thermal probes in tubes below pond
- Diel temperature changes carried downward by seeping water
- Data are recovered after operations, processed to determine rates of fluid seepage
- Co-located with pressure gauges to determine head gradients, derive $K$

Andrew Racz, Graduate Student Researcher
Quantify relations between seepage and phase shift, amplitude reduction (ratio)

\[ \Delta \phi = \text{Phase shift} \]
\[ A_r = \frac{A_d}{A_s} = \text{Amplitude ratio} \]

\[ N \text{ sensors} = 2 \times (N-1)! \text{ pairs} \]
Raw and Filtered Data

Pajaro River, Km 8.06

Measured

Filtered

Water day: 290 310 330 350 370

Measured temperature (°C)

15

10

5

0

Filtered temperature (°C)

24

22

20

18

Water day: 316 317 318

Measured temperature (°C)

Filtered temperature (°C)

z = 10 cm

z = 40 cm
Amplitude ratio ($A_r$)

- Relation depends on sensor spacing, thermal properties
- monotonic (sensitive to both magnitude and direction)
- greatest sensitivity at low specific discharge

\[ \lambda_0 = 1.0 \text{ W/m °C} \]
\[ \beta = 1 \text{ mm} \]

modified from Hatch et al., (2006)
Whole pond infiltration decreases from 1 m/d to 0.1 m/d after 10 weeks.

Infiltration rate decreases in some locations, increases in other areas.
Differences in infiltration rates with location and time

Area of most rapid infiltration migrates from NW to SE across pond

- Whole pond infiltration decreases from 1 m/d to 0.1 m/d after 10 weeks.
- Infiltration rate decreases in some locations, increases in other areas.
Spatially variable and dynamic infiltration

15 January 2008
MAR day 5

modified from Racz et al. (2011)
Spatially variable and dynamic infiltration

30 January 2008
MAR day 20

modified from Racz et al. (2011)
Spatially variable and dynamic infiltration

14 February 2008
MAR day 35

modified from Racz et al. (2011)
Spatially variable and dynamic infiltration

29 February 2008
MAR day 50

modified from Racz et al. (2011)
Spatially variable and dynamic infiltration

14 March 2008
MAR day 65

modified from Racz et al. (2011)
Spatially variable and dynamic infiltration

29 March 2008
MAR day 80

modified from Racz et al. (2011)
Calculating hydraulic conductivity (K)

- Pressure probes in piezometers, stilling well and atmosphere; used to calculate $dH$
- $dz$ is depth from sediment surface to screen
- $q$ is calculated from thermal data
- **Solve for $K$!**

\[
q = -K \frac{dH}{dz}
\]

From thermal probes

\[
\Psi_{\text{piez}} = \frac{P_{\text{piez}}}{\rho_w g}
\]

\[
H_{\text{piez}} = \Psi_{\text{piez}} + z_{\text{piez}}
\]

\[
dH = H_{\text{pond}} - H_{\text{piez}}
\]

\[
\Delta H = \text{pond via rating curve}
\]

WY 2008
**Saturated hydraulic conductivity varies with time**

Hydraulic conductivity ($cm/s$) varies with time for three periods with different behavior:

1. $K$ increases
2. $K$ decreases
3. $K$ stabilizes

modified from Racz et al. (2011)
Saturated hydraulic conductivity varies with time

Hydraulic conductivity (cm/s)

Hydraulic conductivity

Saturated hydraulic conductivity varies with time

Three periods with different behavior

① $K$ increases  ② $K$ decreases  ③ $K$ stabilizes

modified from Racz et al. (2011)
Why does hydraulic conductivity change so much so rapidly?

- Settling of fine sediments on base of pond?
- Infiltration of fine sediments into shallow sediments?
- Soil consolidation resulting from loading?
- Biological fouling in shallow sediments?

\[
K_{\text{eff}} = \frac{\Delta z_{\text{total}}}{\sum_{i=1}^{n} \frac{z_i}{K_i}}
\]
Fluid sampling to assess changes in water quality as a function of infiltration rate, other parameters

Thermal monitoring tube

Fluid sampling lines

Piezometers for fluid sampling

-0.5 m

-1.0 m

24–36 sample locations

Calla Schmidt, Ph.D.
Nitrate concentration is reduced during infiltration

Schmidt et al. (2011a)
Nitrate load is reduced as well.

Load reduction of ~50%, (600 kg of nitrate-N)

Schmidt et al. (2011a)
Infiltration rate (m/d)

Days of MAR

Infiltration rate % NO\textsubscript{3} removed

Percent of NO\textsubscript{3} removed

modified from Schmidt et al. (2011b)
Denitrification and assimilation are most likely mechanisms of nitrate removal.

Idealized nitrogen cycle
Denitrification and assimilation are most likely mechanisms of nitrate removal

Encourage denitrification:
- low oxygen
- high nitrate
- high organic carbon

\[
4\text{NO}_3^- + 5\text{CH}_2\text{O} + 4\text{H}^+ \rightarrow 5\text{CO}_2 + 2\text{N}_2 + 7\text{H}_2\text{O}
\]
Isotopic signature of denitrification

\[ \delta (\permil) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000 \]

\[ R = ^{15}\text{N}/^{14}\text{N} \text{ or } ^{18}\text{O}/^{16}\text{O} \]
Isotopic data are consistent with net denitrification

\[
\delta \left( \%_o \right) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000
\]

\[R = \frac{^{15}\text{N}}{^{14}\text{N}} \text{ or } \frac{^{18}\text{O}}{^{16}\text{O}}\]

Pond Piezometers

data from Schmidt et al. (2011a)
Denitrification rate increases with infiltration rate \((\leq 0.8 \text{ m/d})\)

- \([\text{NO}_3^-]\) < 50 μM
- \([\text{NO}_3^-]\) > 50 μM

\[ R / [\text{NO}_3^-] = \frac{100\% \text{ removal}}{100\%} = 0.72 \]

Denitrification rate increases with infiltration rate \((\leq 0.8 \text{ m/d})\)
moved from Schmidt et al. (2011b)
Comparison to other GW Systems

- \( N_2 \) gradient
- \( \text{NO}_3 \) gradient
- injected \( \text{NO}_3 \) tracer

★ Harkins Slough MAR

Maximum Rate of Denitrification (\( \mu \text{mol L}^{-1} \text{d}^{-1} \))

modified from Green et al. (2006)
Maximum Rate of Denitrification ($\mu$mol L$^{-1}$ d$^{-1}$)

Comparison to other GW Systems

- $N_2$ gradient
- $\text{NO}_3$ gradient
- injected $\text{NO}_3$ tracer

★ Harkins Slough MAR

HS MAR average

modified from Green et al. (2006)
Denitrification is not carbon limited in this system

- Organic carbon available in diverted wetland water
- Organic carbon required to remove observed nitrate load
Summary and conclusions

• Managed aquifer recharge will be increasingly important in California as a strategy for sustaining and improving groundwater resources.
• MAR can result in spatially and temporally variable infiltration.
• Large changes in the hydraulic conductivity of shallow soils during MAR can occur at timescales of days to months.
• Water available for MAR is not always pristine
• MAR can accomplish nitrate load reduction during infiltration.
• Denitrification can occur at rapid rates during shallow infiltration associated with MAR.
• Denitrification can occur more rapidly during faster infiltration, up to a threshold (in our study, ~0.6 to 0.8 m/d – other sites?).
• There may be a "sweet spot" for MAR operations that allows simultaneous achievement of water supply and water quality improvement goals.
Many thanks to additional project collaborators, advisors…

C. Geoff Wheat, Jonathan Lear, Tess Russo, Carol Kendall, Adina Paytan, Ivano Aiello, Erick Castillo, John Vesecky, Steve Peterson

…and those providing field, lab, technical assistance…

Susie Bird, Allison Regelado, Nic Massetani, Joanna Hoffman, Rick Ednie, Rob Franks, Dyke Andreasen, Dan Sampson

…and funding
Thank you!

Questions?

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