# Vulnerability of Groundwater Resources Underlying Unlined Produced Water Ponds in the Tulare Basin of the San Joaquin Valley, California

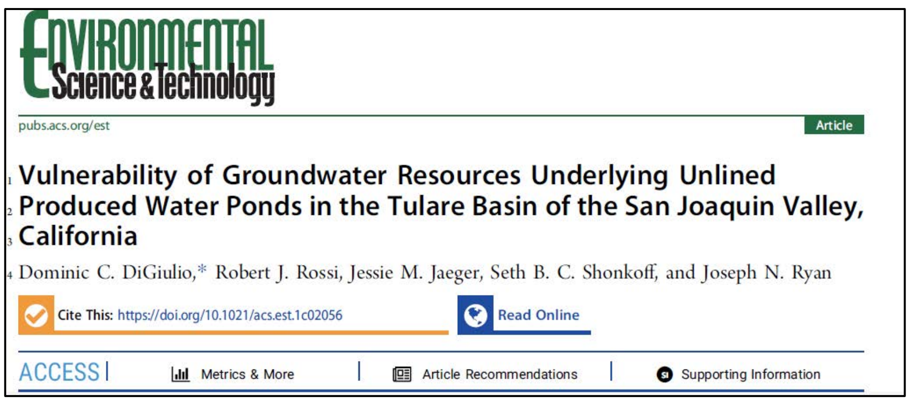

Dominic C. DiGiulio[1,2], Robert J. Rossi[1], Jessie M. Jaeger[1], Seth B.C. Shonkoff[1,3,4], Joseph N. Ryan[2]

[1] PSE Healthy Energy, Oakland, CA

[2] Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CO

[3] Department of Environmental Science, Policy, Management, University of California, Berkeley, CA

[4]Lawrence Berkeley National Laboratory, Berkeley, CA


Environmental Science & Technology

pubs.acs.org/est Article

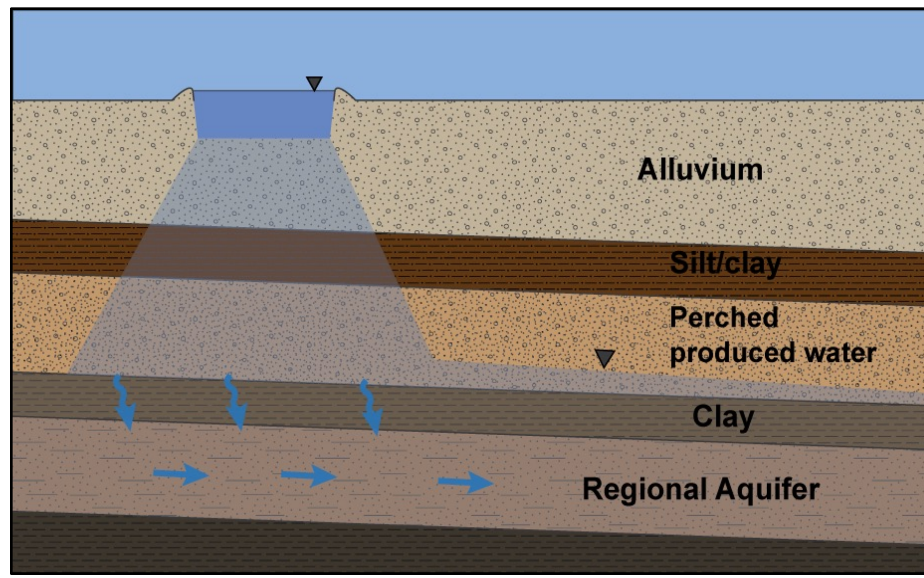

Vulnerability of Groundwater Resources Underlying Unlined Produced Water Ponds in the Tulare Basin of the San Joaquin Valley, California


Dominic C. DiGiulio,* Robert J. Rossi, Jessie M. Jaeger, Seth B. C. Shonkoff, and Joseph N. Ryan



Cite This: https://doi.org/10.1021/acs.est.1c02056 Read Online


ACCESS | Metrics & More | Article Recommendations | Supporting Information



# About PSE

**Physicians, Scientists, and Engineers (PSE) for Healthy Energy** is an energy science and policy research institute focused on the public health, climate, and environmental dimensions of energy production and use.

We conduct original research, translate existing research for non-technical audiences, and disseminate scientific information and analyses to inform policy at the local, state, and federal levels.

# Introduction

# Tulare Basin

- The San Joaquin Valley occupies the southern two-thirds of the Central Valley.
- The San Joaquin Valley is separated into the San Joaquin Basin to the north and the Tulare Basin to the south.
- ~99% of unlined produced water ponds in California are in the Tulare Basin.

Sustained droughts and continued groundwater depletion in the San Joaquin Valley has highlighted the need to protect remaining groundwater resources from degradation associated with industrial practices including those associated with oil and gas development.

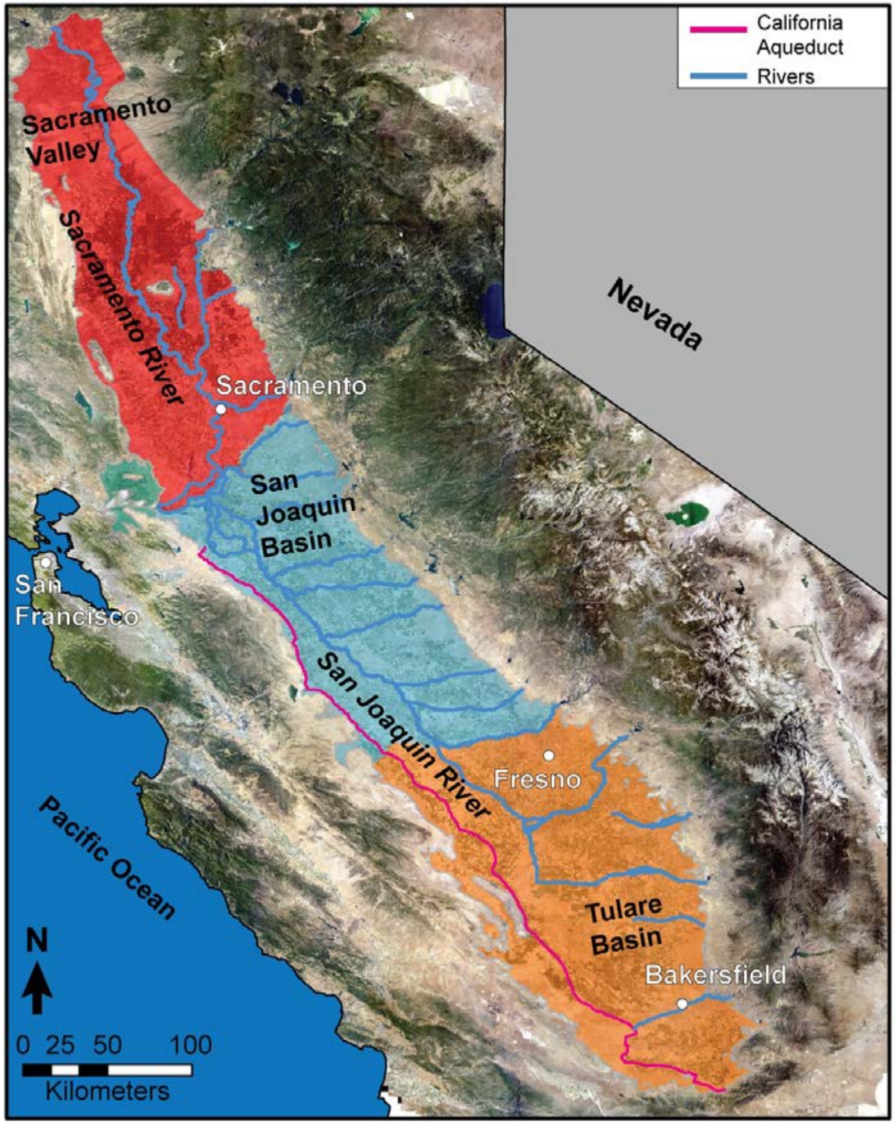
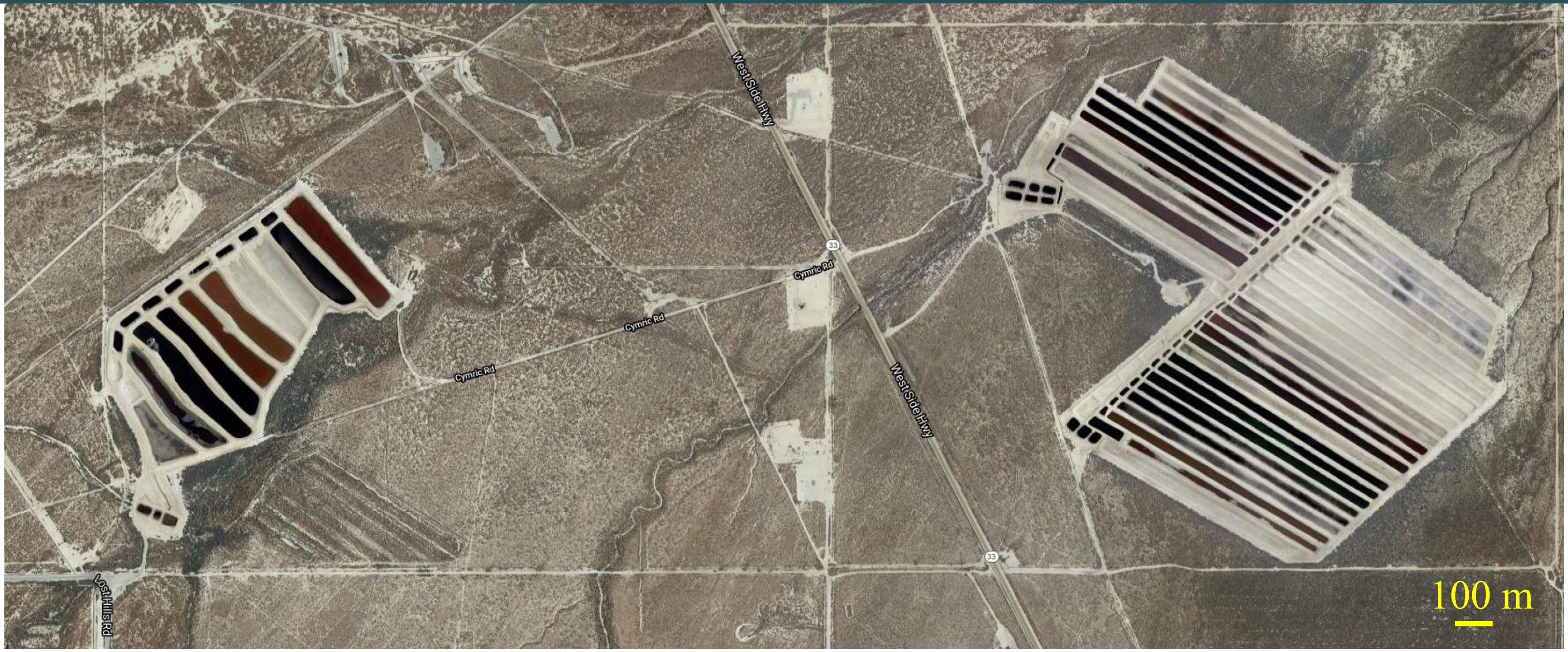



Figure from DiGiulio et al. 2021 (ES&T).

# Disposal Practice Dating Back to 1900




Aerial image of the McKittrick 1-1 and 1 & 1-3 Facilities. Image from Geotracker.

One area of growing concern is the impact to groundwater resources from ongoing and historical disposal of produced water into unlined produced water ponds.

This disposal practice has occurred in the Tulare Basin since at least 1900.

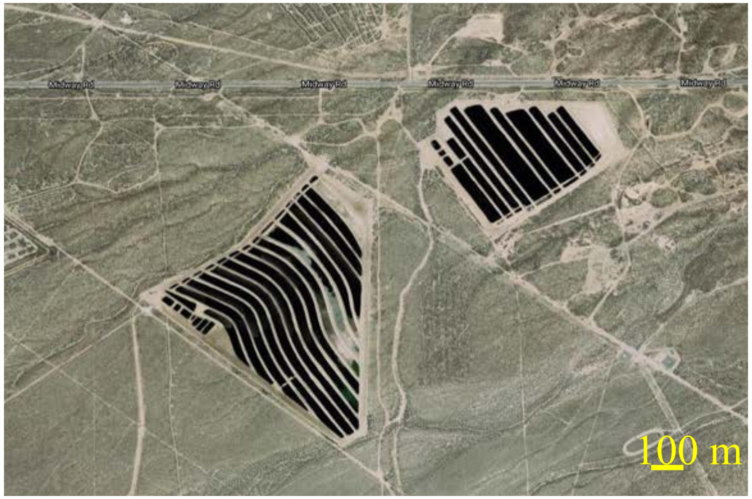
Impact to groundwater from disposal of produced water into unlined impoundments is well documented.



PSE

# Classification of Produced Water Ponds

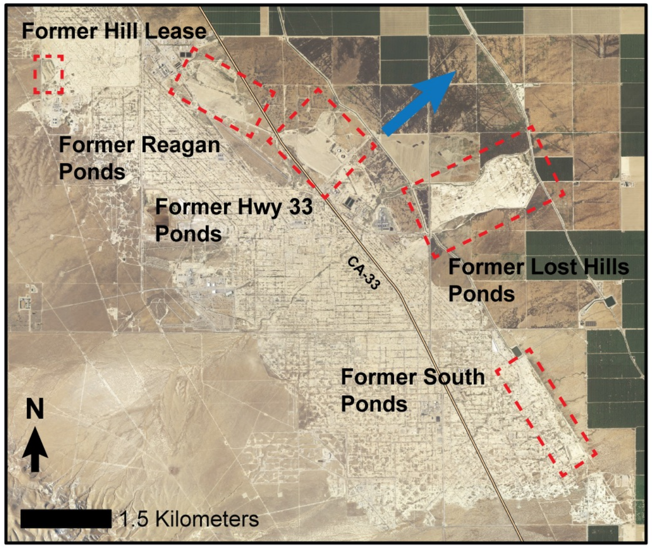
An active produced water pond facility currently receives produced water.




Aerial image of the Broad Creek 2 Facility from Geotracker

An inactive produced water pond facility has a physical connection to a produced water source but does not currently receive produced water.

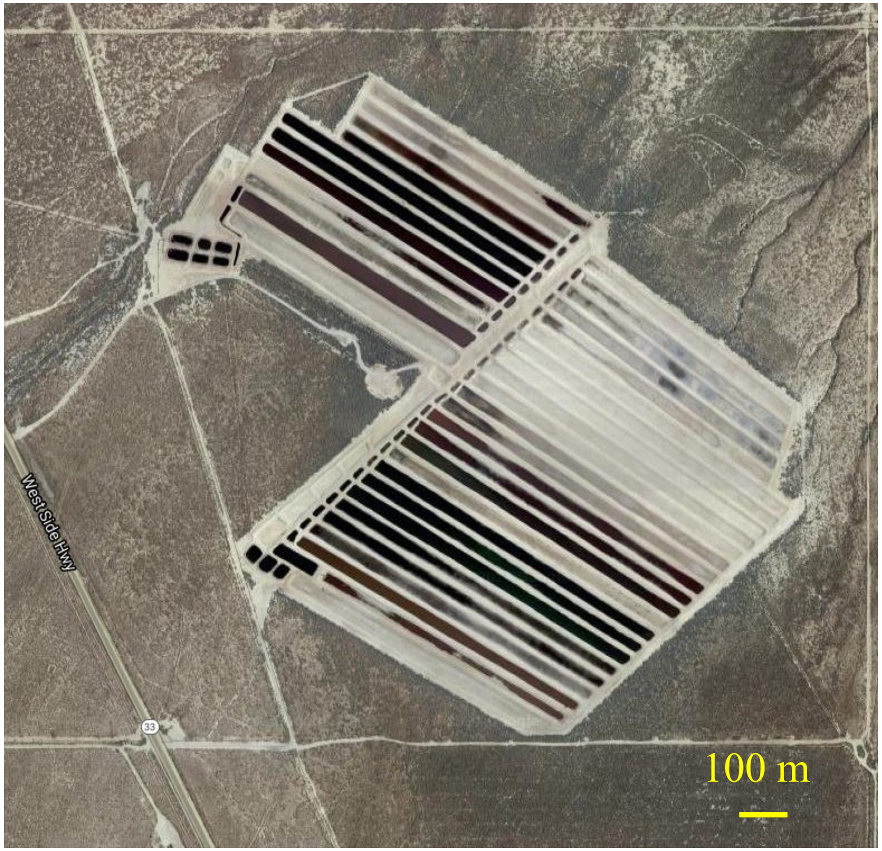

Aerial image of McKittrick 6A, 6B from Geotracker




Closed Facilities.

Figure from DiGiulio et al. (2021)

# Treatment Prior to Discharge



Aerial image of the McKittrick 1 & 1-3 Facilities. Image from Geotracker.

Prior to discharge to unlined ponds, produced water may be treated with emulsion breakers, surfactants, clarifiers, and other additives to facilitate oil/water separation.

In large complexes, produced water enters smaller unlined ponds that provide for additional floatation and skimming of remaining undissolved oil prior to flowing into larger unlined ponds for evaporation and percolation.

Only 0.25% of produced water discharged to unlined ponds is treated beyond deoiling.

| Treatment (as reported under SB 1281, 2014-2017) | San Joaquin Valley (%) |
| --- | --- |
| Deoiling | 94.87 |
| Deoiling + Other Treatment | 0.25 |
| No Method | 2.06 |
| Membrane Treatment | 0.00003 |
| Desalination | 0 |
| Untreated | 2.82 |

# Methods and Trends of Produced Water Disposal

The primary method of produced water management has been and remains underground injection for enhanced oil recovery and disposal.

However large volumes of produced water have been disposed in unlined produced water ponds, especially prior to 2014.

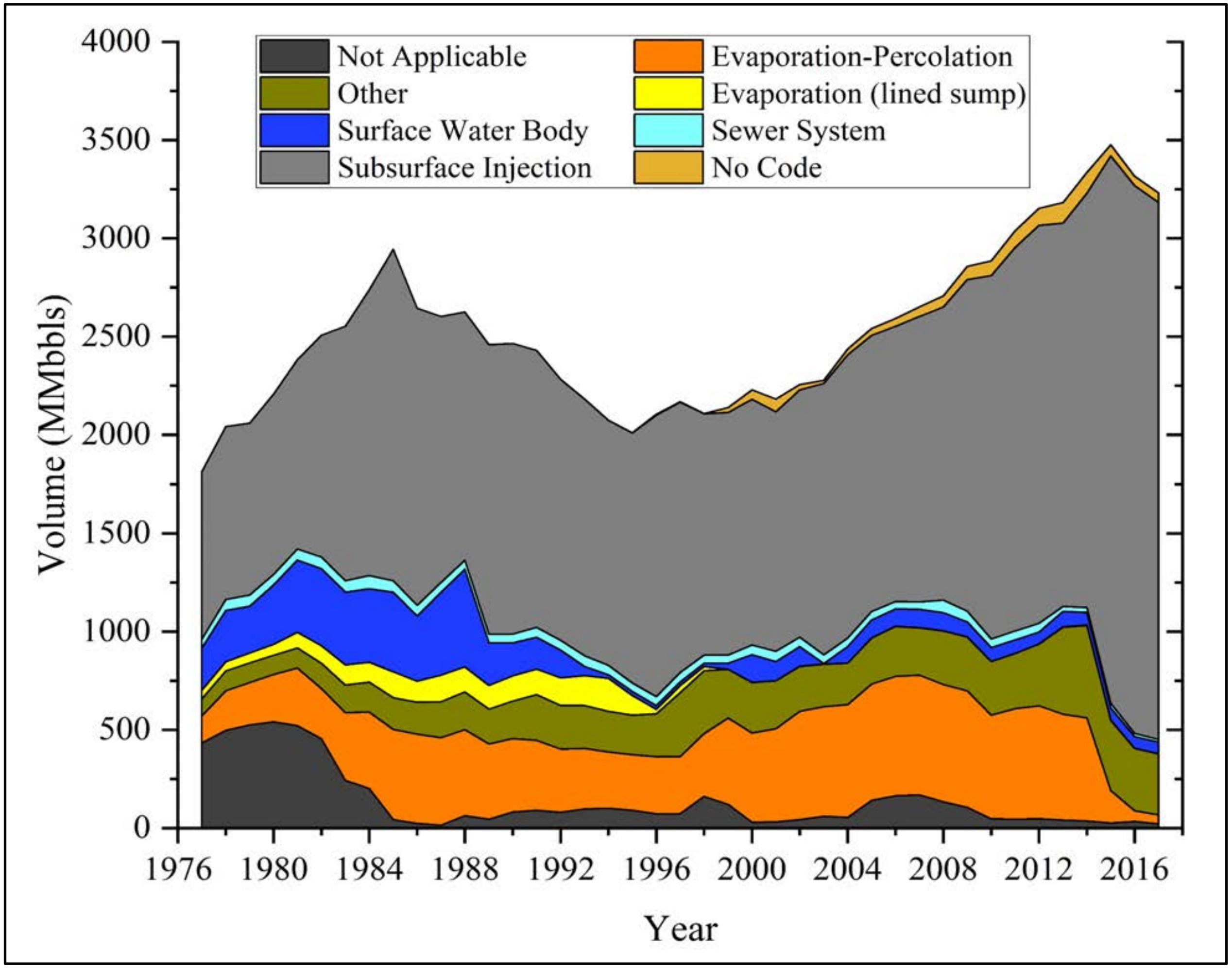



Figure from DiGiulio et al. (2021).

# Cumulative Surface Disposal Volumes

Between 1977 and 2017, over 16 billion barrels of produced water were disposed in unlined produced water ponds representing a potential wide-scale legacy groundwater contamination issue.

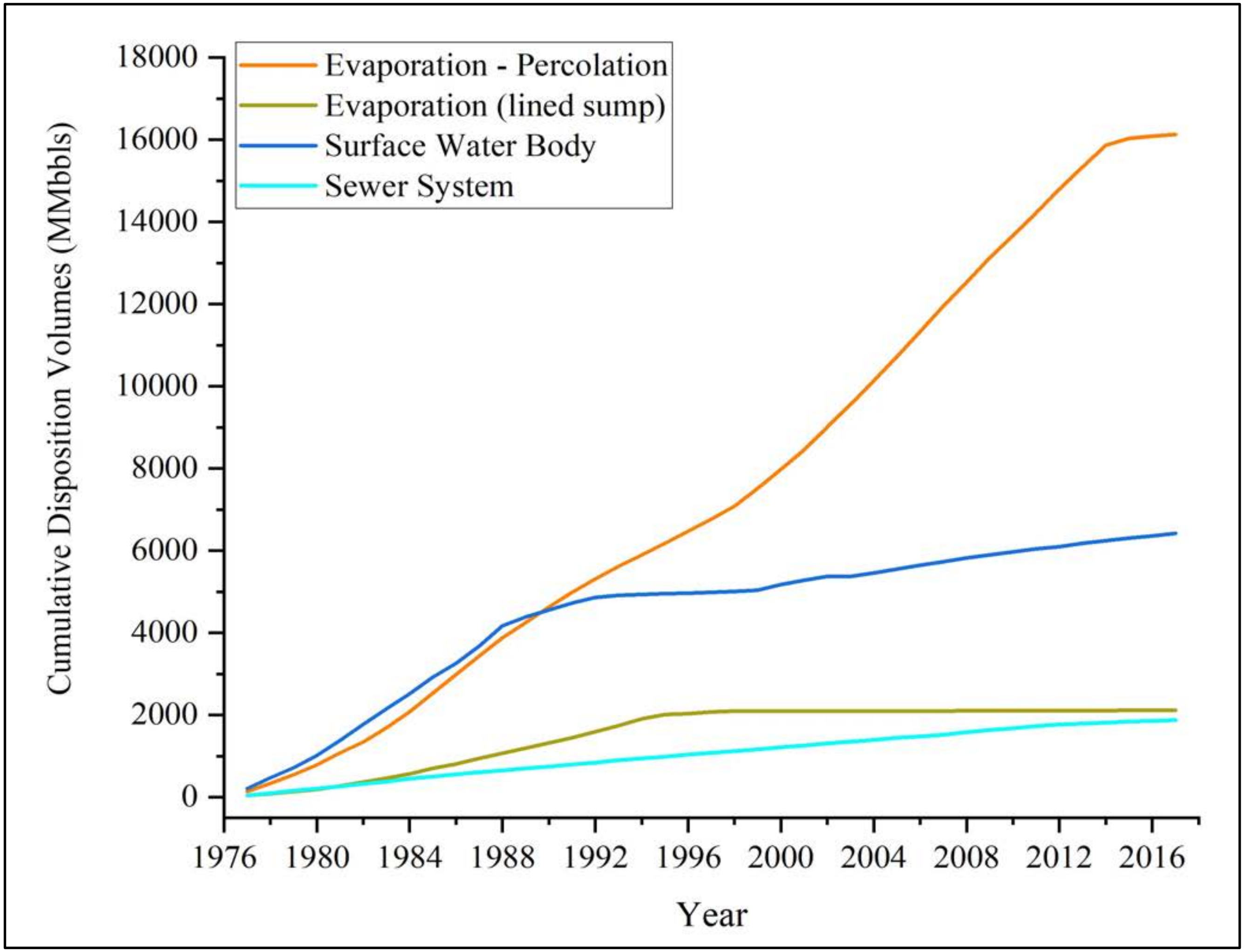
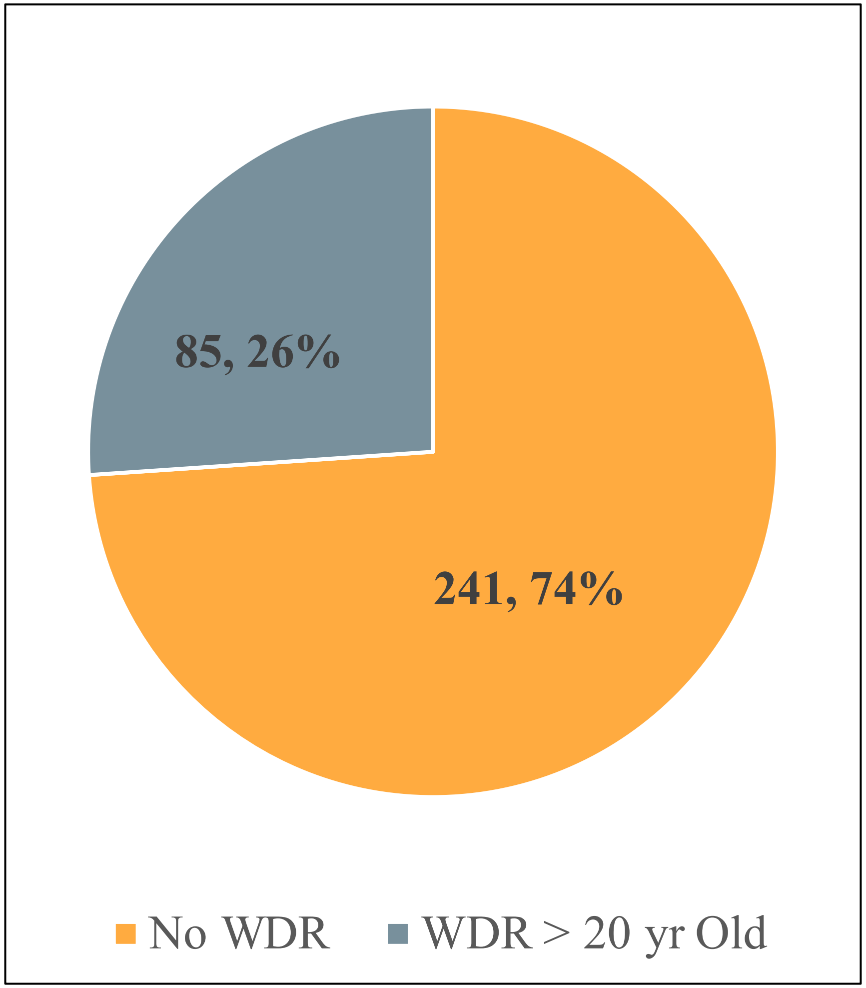



Figure from DiGiulio et al. (2021).

PSE

# Increased Regulatory Effort After 2014

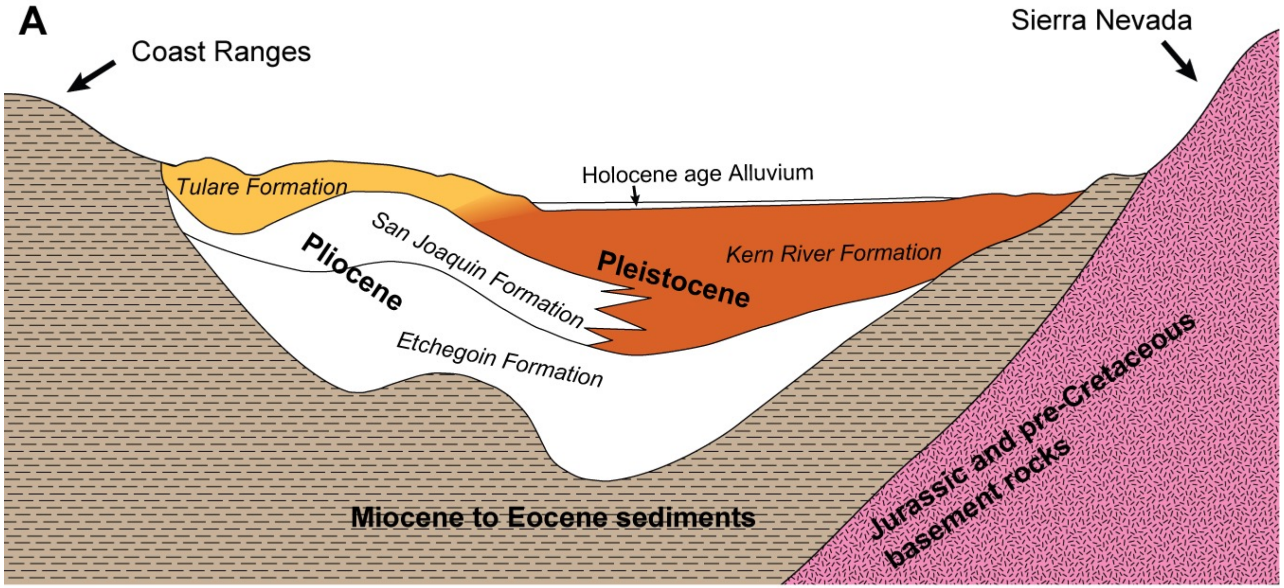
In May 2014, the Central Valley Regional Water Quality Control Board began an effort to better regulate unlined produced water ponds. They located 326 facilities with 1,100 produced water ponds.






PSE

# Formations Having Groundwater Resources




(a) Generalized cross-section of the southern San Joaquin Basin created using information from Gautier and Hosford Scheirer (2007). (b) Inset map illustrating the approximate location of generalized cross-section. Figure from DiGiulio et al. (2021) (ES&T).


Groundwater resources are primarily present in alluvial deposits, Kern River Formation, and Tulare Formation.

Groundwater in the Kern River Formation is primarily calcium bicarbonate type reflecting weathering from the Sierra Nevada.

In the western portion of the basin, groundwater in the Tulare Formation is calcium/sodium sulfate type water.

In general, levels of total dissolved solids (TDS) increase from east to west as bicarbonate is replaced by sulfate and to a lesser extent chloride.

PSE

# Definition of Protected Groundwater

| Maximum TDS (mg/L) | Applicability to O&G Industry | Enforceability | Overseeing Agencies |
|---|---|---|---|
| **3,000 mg/L or EC < 5,000 µS/cm for municipal water supply (MUN)** | Land disposal, produced water ponds | *States Sources of Drinking Water Policy* (SWRCB Res No. 88-63 (SWRCB 2006). TDS and EC not defined for other beneficial use such as that used for agriculture (AGR). | SWRCB |
| **Undefined** | Conventional O&G Development | PRC § 1722.22 for casing requirements | CalGEM |
| **10,000** | Well stimulation | CA Water Code § 10783(k)(2) | CalGEM, SWRCB |
| **10,000** | UIC Program | USDW, protected unless exempted, 40 C.F.R. 144.3 | EPA, CalGEM |
| **10,000** | O&G development on federal or tribal land | Onshore Oil & Gas Order No. 2, 53 Federal Register 46798 | BLM, CalGEM, SWRCB |

In the State's Sources of Drinking Water Policy, one criterion used to determine the suitability of groundwater for domestic or municipal beneficial use is groundwater having a TDS concentration < 3000 mg/L or EC < 5000 µS/cm. There is not a TDS criterion or numerical standards for protection of groundwater having agricultural or other beneficial use.

There is no explicit protection of groundwater having TDS levels > 3000 mg/L underlying or in the vicinity of produced water ponds.

This is inconsistent with and less stringent than protection of groundwater in the UIC program as required by EPA pursuant to the SDWA and during well stimulation in California (e.g., hydraulic fracturing) where groundwater is explicitly protected to a level of 10000 mg/L TDS.

**A more detailed discussion of state policies regarding groundwater having beneficial use is discussed in Supporting Information.**

# Basis for Protected Groundwater Definition

LLNL-TR-669645

LAWRENCE LIVERMORE NATIONAL LABORATORY

***Recommendations on Model Criteria for Groundwater Sampling, Testing, and Monitoring of Oil and Gas Development in California***

Bradley K. Esser[1], Harry R. Beller[2], Susan A. Carroll[1], John A. Cherry[3], Jan Gillespie[4], Robert B. Jackson[5], Preston D. Jordan2, Vic Madrid[1], Joseph P. Morris[1], Beth L. Parker[3], William T. Stringfellow[2], Charuleka Varadharajan[2], and Avner Vengosh[6]

[1]*Lawrence Livermore National Laboratory, Livermore, California*
[2]*Lawrence Berkeley National Laboratory, Berkeley, California*
[3]*University of Guelph, Guelph, Canada*
[4]*California State University, Bakersfield, California*
[5]*Stanford University, Stanford, California*
[6]*Duke University, Durham, North Carolina*

**June, 2015**

**Final Report**
**California State Water Resources Control Board**

State of California Contract 14-050-250;
LLNL Work for Others Proposal L15606

**Reasons to Maintain a Definition of Protected Groundwater Equivalent to an USDW During Well Stimulation in California**

Seth B.C. Shonkoff, MPH, Ph.D., PSE Healthy Energy
Dominic C. DiGiulio, Ph.D., PSE Healthy Energy

Presented at:

The California State Water Resources Control Board Public Meeting on:

Staff Workshop Review of Model Criteria for Groundwater Monitoring in Areas of Oil and Gas Well Stimulation Definition of "Protected Water"

Sacramento, CA
May 10, 2019

PSE Bringing science to energy policy

The panel stated monitoring at 10,000 mg/L TDS is appropriate because it aligns with EPA's UIC program and is "technically and economically feasible to desalinate" water at this level of salinity (Esser et al. 2015).

PSE

# Objectives of Investigation

The objective of this investigation was to determine whether past and present disposal of produced water into unlined produced water ponds poses a risk to groundwater resources in the Tulare Basin. To achieve this objective, we:

(1) determined the number, status, and locations of produced water ponds in the Tulare Basin,
(2) compiled available information on the composition of produced water discharged into produced water ponds,
(3) estimated levels of total dissolved solids (TDS) in groundwater underlying and in the vicinity of unlined produced water pond locations, and
(4) summarized locations where groundwater monitoring well data indicate impact to groundwater resources in the Tulare Basin from this disposal practice.



PSE

# Methods

# Number and Locations of Produced Water Ponds




Reviewed all available files to 12/31/2019.

Visually examined ponds on Google Earth.

Reviewed groundwater investigations where available.

Compiled data on chemical characterization of produced water in ponds (most in pdf).

# TDS Levels in Groundwater Having Coordinates


6,974 Municipal and domestic wells.


1,985 Municipal and domestic wells.


2,282 Municipal and domestic wells.

1,126 production wells (provided information of water resources with depth).

Only used data where information was available on depth.

Water wells considered here (11,241) are a subset of wells in the Tulare Basin. Most water wells in California are identified as a centroid in the Public Land Survey System (~650 acre area). Insufficient information for a domestic well proximity analysis.

Used algorithm, inverse distance to a power (n=2) to contour levels of total dissolved solids.

# Results and Discussion

# Produced Water Database in Tulare Basin

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z | AA | AB | AC | AD | AE | AF | AG | AH | AI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Field Name | Field Code | Lease Name | Operator | GeoTracker GlobalID/ Order No. | Number of Ponds | On SWRCB Ponds List, Yes=1, No=0 | In GeoTracker, Yes=1, No=0 | In Well Star, Yes=1 | Pond Status | Sec | Twp | Range | County | Latitude | Longitude | Est. Lat, Long from PLSS, Y=1, No = 0 | Irrigation Pond | Unlined Active Pond | Unlined Inactive Pond | Unlined Closed Pond | Lined Active Pond | Lined Inactive Pond | Lined Closed Pond | Lined or Unlined Inactive Pond | Lined or Unlined Active Pond | Lined or Unlined Closed | Unidentified | Ponds per Facility for Plotting | Status of Ponds for Plotting | Centroid of Facility for Plotting - Latitude | Centroid of Facility for Plotting - Longitude | Pond Data | Groundwater Data | Groundwater Subbasin |
| 1366 | Semitropic | 690 | Supreme | Carneros Energy | L10006216376 | 1 | 0 | 1 | | Closed | 14 | 27S | 23E | Kern | 35.571931 | -119.47424 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.5719312 | -119.47424 | no | no | Kern |
| 1367 | Semitropic | 690 | USL | California Resources Production Corporation | L10006410854 | 1 | 1 | 1 | | Closed | 22 | 27S | 23E | Kern | 35.57151 | -119.47566 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | | 1 | closed | 35.57151 | -119.47566 | no | no | Kern |
| 1368 | Semitropic | 690 | Williams Elliot-15 | Carneros Energy | L10003664008 | 1 | 0 | 1 | | Closed | 15 | 27S | 23E | Kern | 35.575399 | -119.47466 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.5753986 | -119.47466 | no | no | Kern |
| 1369 | Semitropic | 690 | Williams Elliot-24 | Carneros Energy | L10008264964 | 1 | 0 | 1 | | Closed | 24 | 27S | 23E | Kern | 35.561741 | -119.45042 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.5617413 | -119.45042 | no | no | Kern |
| 1370 | Stockdale | 786 | Panama | Crimson Resource Management | L10006481569 o | 1 | 1 | 1 | | Inactive | 14 | 30S | 27E | Kern | 35.31087 | -119.05128 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, inactive | 35.31087 | -119.05128 | no | no | Kern |
| 1371 | Stockdale | 786 | Tenneco | Crimson Resource Management | L10003853167 | 1 | 1 | 1 | | Inactive | 15 | 30S | 27E | Kern | 35.31504 | -119.06386 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, inactive | 35.31504 | -119.06386 | no | no | Kern |
| 1372 | Strand | 787 | Posuncula KCL | ? | L10009651722 | 2 | 0 | 2 | | closed | 12 | 30S | 25E | Kern | 35.336041 | -119.24051 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | | 2 | unlined, closed | 35.3360406 | -119.24051 | no | no | Kern |
| 1373 | Strand | 787 | Shell-Ohio | ? | L10009628444 | 8 | 0 | 8 | | inactive | 12 | 30S | 25E | Kern | 35.332391 | -119.24349 | 1 | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 8 | unlined, inactive | 35.3323913 | -119.24349 | no | no | Kern |
| 1374 | Tejon | 752 | JV | California Resources Production Corporation | ? | 1 | 1 | 0 | | Inactive | 32 | 11N | 19W | Kern | ? | ? | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, inactive | ? | ? | no | no | Kern |
| 1375 | Tejon | 752 | JV-32 | Stockdale Oil & Gas | L10001758719 | 7 | 0 | 7 | | inactive | 32 | 11N | 19W | Kern | 34.988582 | -118.92606 | 0 | 0 | 0 | 3 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | | 7 | unlined, inactive | 34.988582 | -118.92606 | no | no | Kern |
| 1376 | Tejon | 752 | OMB-33 | Stockdale Oil & Gas | ? | 1 | 0 | 1 | | closed | 33 | 11N | 19W | Kern | 34.990042 | -118.9112 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 34.9900416 | -118.9112 | no | no | Kern |
| 1377 | Tejon | 752 | Section 32 | Stockdale Oil & Gas | L10003819252 | 7 | 0 | 7 | | closed | 32 | 11N | 19W | Kern | 34.986763 | -118.92931 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 3 | 0 | 0 | 0 | | 7 | unlined, closed | 34.9867634 | -118.92931 | no | no | Kern |
| 1378 | Tejon | 752 | Transition | California Resources Production Corporation | ? | 1 | 1 | 0 | | Closed | 32 | 11N | 19W | Kern | 34.98667 | -118.93008 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 34.98667 | -118.93008 | no | no | Kern |
| 1379 | Tejon SE | 752 | SCT | Drilling & Production Company | L10002222565 | 1 | 1 | 1 | | inactive | 12 | 10N | 19W | Kern | 34.96601 | -118.86193 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, inactive | 34.96601 | -118.86193 | no | no | Kern |
| 1380 | Tejon Hills | 756 | Roco Lease (A) | Steele Petroleum Company | L10003550937 | 1 | 0 | 1 | | closed | 15 | 11N | 18W | Kern | 35.036971 | -118.78749 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.0369711 | -118.78749 | no | no | Kern |
| 1381 | Tejon Hills | 756 | Roco Lease (B) | Steele Petroleum Company | L10004633346 | 1 | 0 | 1 | | closed | 15 | 11N | 18W | Kern | 35.039986 | -118.78505 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.0399862 | -118.78505 | no | no | Kern |
| 1382 | Tejon Hills | 756 | Roco Lease (C) | Steele Petroleum Company | L10003223363 | 1 | 0 | 1 | | closed | 15 | 11N | 18W | Kern | 35.041796 | -118.78054 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.0417963 | -118.78054 | no | no | Kern |
| 1383 | Tejon Hills | 756 | Sunset-Tejon 10 | Havens Oil Company | T10000006814 | 1 | 1 | 1 | | inactive | 11 | 11N | 18W | Kern | 35.05565 | -118.76873 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | no | no | Kern |
| 1384 | Tejon Hills | 756 | Sunset-Tejon 10 | Havens Oil Company | T10000006814 | 1 | 1 | 1 | | inactive | 10 | 11N | 18W | Kern | 35.05151 | -118.77922 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 2 | unlined, inactive | 35.05358 | -118.77398 | no | no | Kern |
| 1385 | Tejon Hills | 756 | Sunset-Tejon 15 | Havens Oil Company | ? | 1 | 1 | 0 | | inactive | 15 | 11N | 18W | Kern | 35.04365 | -118.78165 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, inactive | 35.04365 | -118.78165 | no | no | Kern |
| 1386 | Tejon Hills | 756 | Tejon Ranch 22 | Chevron Texaco Exploration & Development | L10007621397 | 1 | 0 | 1 | | closed | 21 | 11N | 18W | Kern | 35.019164 | -118.80428 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.0191644 | -118.80428 | no | no | Kern |
| 1387 | Tejon North | 758 | KCL | Polaris Production Inc | L10008455577 | 1 | 0 | 1 | | inactive | 25 | 11N | 20W | Kern | 35.011932 | -118.95838 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, inactive | 35.0119317 | -118.95838 | no | no | Kern |
| 1388 | Temblor Ranch | 762 | Delanty | LDD Energy, LLC | ? | 1 | 1 | 0 | | inactive | 36 | 29S | 20E | Kern | 35.3623 | -119.77139 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | | | | | | no | no | Kern |
| 1389 | Temblor Ranch | 762 | Delanty | LDD Energy, LLC | ? | 1 | 1 | 0 | | inactive | 36 | 29S | 20E | Kern | 35.36253 | -119.77119 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | | 2 | inactive | 35.362415 | -119.77129 | no | no | Kern |
| 1390 | Ten Section | 766 | KCL 59 | California Petroleum Group Inc. | ? | 1 | 0 | 0 | 1 | Removed | ? | ? | ? | Kern | 35.29997 | -119.23914 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | | | | | | | | |
| 1391 | Ten Section | 766 | KCL 59 | California Petroleum Group Inc. | ? | 1 | 0 | 0 | 1 | Removed | ? | ? | ? | Kern | 35.30022 | -119.23908 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | | 2 | closed | 35.300095 | -119.23911 | | | |
| 1392 | Valpredo | 808 | SP 48 | Havens Oil Company | ? | 1 | 1 | 0 | | inactive | 35 | 12N | 19W | Kern | 35.08068 | -118.8708 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | | | | | | no | no | Kern |
| 1393 | Valpredo | 808 | SP 48 | Havens Oil Company | ? | 1 | 1 | 0 | | inactive | 35 | 12N | 19W | Kern | 35.08055 | -118.8708 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | | 2 | inactive | 35.080615 | -118.8708 | no | no | Kern |
| 1394 | Wasco | 822 | Mushrush | Bennett Petroleum | L10007393549 | 1 | 0 | 1 | | closed | 7 | 27S | 24E | Kern | 35.594951 | -119.42981 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.5949509 | -119.42981 | no | no | Kern |
| 1395 | Welcome Valley | 826 | Mackessy | E&B Natural Resources Management Corporation | L10004263820 | 1 | 1 | 1 | | inactive | 7 | 26S | 19E | Kern | 35.68117 | -119.96698 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, inactive | 35.68117 | -119.96698 | no | no | Kern |
| 1396 | Welcome Valley | 826 | Sun Mayberry | McAdams Arthur | L10009251743 | 1 | 0 | 1 | | closed | 1 | 26S | 18E | Kern | 35.691893 | -119.97517 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 | unlined, closed | 35.6918931 | -119.97517 | no | no | Kern |
| 1397 | Wheeler Ridge | 832 | W.R.U. | California Resources Production Corporation | ? | 1 | 1 | 0 | | closed | 28 | 11N | 20W | Kern | 35.01567 | -119.01277 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | | 1 | closed | | | no | no | Kern |
| 1398 | | | | | | 1879 | 1317 | 1213 | 60 | | | | | | | | 110 | 29 | 484 | 529 | 457 | 43 | 36 | 43 | 60 | 27 | 76 | 95 | 1879 | | | | | | |

Excel spreadsheet in supporting information containing a comprehensive database on location and status of produced water ponds in Tulare Basin.

PSE

# Potential Identified Closed Facilities

Potential closed facility west of the Belridge North Field. Figure from Geotracker.

Potential closed facility west of the Belridge North Field. Figure from Geotracker.

Potential closed facility west of the Belridge North Field. Figure from Geotracker.

Potential closed facility in Midway-Sunset Field. Figure from Geotracker.

# Number and Status of Produced Water Ponds

Excluding ponds used to mix produced water with surface and groundwater for irrigation, there appears to be at least 1,850 active, inactive, and closed produced water ponds in the Tulare Basin.

At least 85% (1,565/1,850) of produced water ponds in the Tulare Basin are unlined, of which 31% (484/1,565) are still active.

| Source | Number of Ponds Listed | Number of Ponds Unique to Source |
|---|---|---|
| SWRCB List | 1317 | 511 |
| WellStar | 311 | 60 |
| Geotracker | 1213 | 407 |

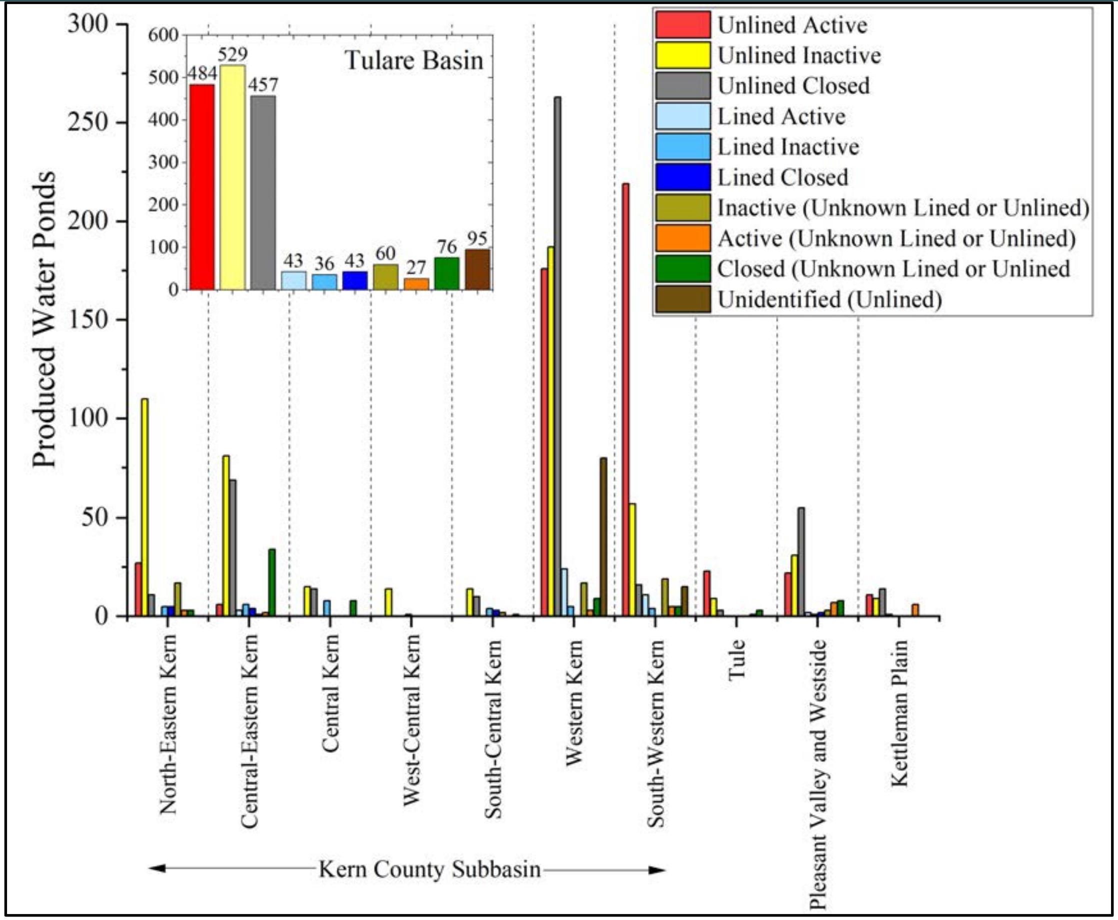



Figure from DiGiulio et al. (2021) (ES&T).

No individual database could accurately account for all produced water ponds. The discrepancy between the SWRCB List and Geotracker is due in part to lack of identification of many closed facilities on the SWRCB List. Other reasons for discrepancies are unclear.

PSE

# Chemical Composition of Water in Ponds

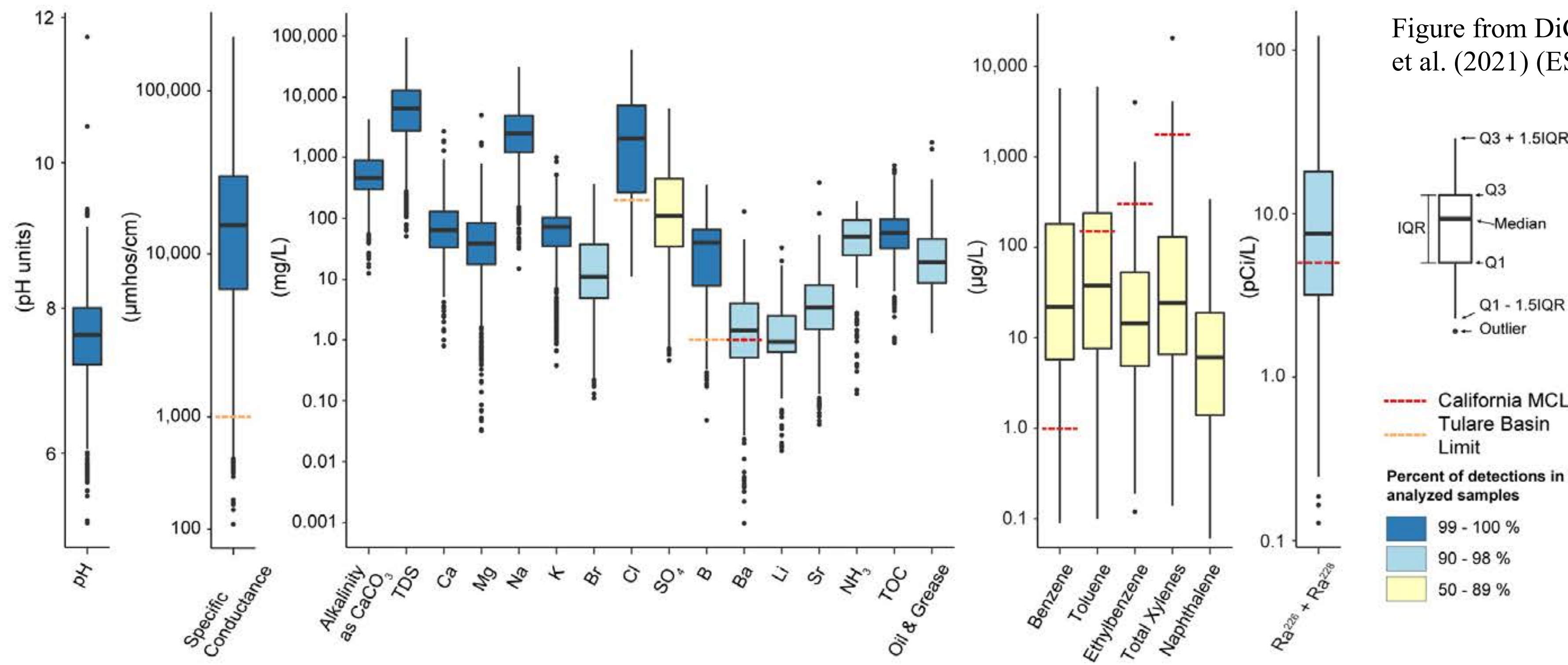



Figure from DiGiulio et al. (2021) (ES&T).

Most samples from larger facilities where multiple sampling events occurred.

Method detection limits (MDLs) were not used to calculate median values. MDLs at times greater than detected concentrations at other times. Only parameters detected at a frequency >50% illustrated. Complete dataset in supporting information.

Effluent limits for discharge into produced water ponds in Tulare Basin are **1,000 µS/cm for specific conductance, 200 mg/L for chloride, and 1 mg/L for boron**. Effluent limits do not exist for other parameters.

Since pH is circumneutral, most ammonia present as ammonium ion.

Detection of organic compounds largely limited to BTEX compounds and naphthalene.

# EC, TDS, Cl, and B Facility Summary

| Field | Lease | EC min (µS/cm) | EC median (µS/cm) | EC max (µS/cm) | n | TDS min (mg/L) | TDS median (mg/L) | TDS max (mg/L) | n | Cl min (mg/L) | Cl median (mg/L) | Cl max (mg/L) | n | B min (mg/L) | B median (mg/L) | B max (mg/L) | n |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northeastern Kern Subbasin** | | | | | | | | | | | | | | | | | |
| Jasmin | Quinn | 600 | 660 | 795 | 28 | 380 | 420 | 540 | 27 | 50 | 57 | 69 | 28 | 0.58 | 0.76 | 1.1 | 28 |
| Kern Front | No. 2 Treatment | 220 | 780 | 1100 | 30 | 150 | 515 | 750 | 30 | 25 | 85 | 180 | 30 | 0.22 | 0.84 | 1.2 | 30 |
| | Pedro USL | NA | NA | NA | 0 | ----- | ----- | 6400 | 1 | ----- | ----- | 1400 | 1 | ----- | ----- | 7.9 | 1 |
| | Signal | 540 | 550 | 1800 | 6 | 320 | 375 | 1000 | 4 | 53 | 59 | 380 | 6 | 0.17 | 0.24 | 1.1 | 6 |
| Kern River | Beardsley and Carrier | 770 | 894 | 930 | 4 | 512 | 573 | 629 | 4 | 108 | 128 | 140 | 4 | 1.1 | 1.4 | 2.2 | 7 |
| Mount Poso | Jones | NA | NA | NA | 0 | ----- | ----- | 600 | 1 | ----- | ----- | 120 | 1 | ----- | ----- | 0.90 | 1 |
| Poso Creek | Desert Glow | NA | NA | NA | 0 | 350 | 360 | 370 | 2 | 43 | 56 | 68 | 2 | 0.89 | 0.91 | 0.93 | 1 |
| | Government | ----- | ----- | 490 | 1 | ----- | ----- | 350 | 1 | ----- | ----- | 60 | 1 | ----- | ----- | 0.65 | 1 |
| | McVan | NA | NA | NA | 0 | ----- | ----- | 860 | 1 | ----- | ----- | 91 | 1 | ----- | ----- | 0.94 | 1 |
| **Central Eastern Kern Subbasin** | | | | | | | | | | | | | | | | | |
| Edison | Claflin | ----- | ----- | 910 | 1 | ----- | ----- | 620 | 1 | ----- | ----- | 100 | 1 | ----- | ----- | 0.8 | 1 |
| | Fee 34 | 3975 | 5800 | 7400 | 25 | 2400 | 3500 | 4250 | 19 | 1200 | 1800 | 2410 | 23 | 6.0 | 13 | 210 | 23 |
| | Lehr | 580 | 740 | 890 | 16 | 425 | 515 | 761 | 10 | 19 | 29 | 78 | 16 | 0.38 | 0.51 | 0.85 | 16 |
| | Racetrack | 960 | 2070 | 4860 | 3 | 630 | 1200 | 3500 | 4 | 110 | 310 | 780 | 4 | 1.0 | 2.5 | 6.2 | 4 |
| | Race Track Hill | 4300 | 6500 | 9800 | 35 | 2400 | 3670 | 6600 | 35 | 1300 | 2010 | 3300 | 37 | 8.8 | 14 | 240 | 36 |
| **Western Kern Subbasin** | | | | | | | | | | | | | | | | | |
| Asphalto | CA Federal A | NA | NA | 52300 | 1 | ----- | ----- | 32100 | 1 | ----- | ----- | 14500 | 1 | ----- | ----- | 148 | 1 |
| | Ferguson | 48000 | 49300 | 50600 | 2 | 30000 | 30530 | 31060 | 2 | 16000 | 16035 | 16070 | 2 | 110 | 129 | 147 | 2 |
| | Standard | 51000 | 52000 | 53000 | 2 | 32000 | 33000 | 34000 | 2 | 18000 | 19500 | 21000 | 2 | 150 | 155 | 160 | 2 |
| Carneros Creek | Anderson | ----- | ----- | 4200 | 1 | ----- | ----- | 3700 | 1 | ----- | ----- | 140 | 1 | ----- | ----- | 2.4 | 1 |
| | Standard | 3900 | 4200 | 4500 | 2 | 2700 | 3635 | 4510 | 2 | 120 | 150 | 180 | 2 | 1.7 | 1.9 | 2.1 | 2 |
| | Santa Fe Energy | 4200 | 4450 | 4700 | 2 | 3700 | 4345 | 4990 | 2 | 140 | 160 | 180 | 2 | 2.4 | 3.0 | 3.6 | 2 |
| | Theta (30) | 4700 | 5350 | 11000 | 4 | 3300 | 5625 | 10400 | 4 | 150 | 170 | 410 | 4 | 2.1 | 2.4 | 2.6 | 4 |
| Chico-Martinez | Mitchel | 5500 | 10300 | 58900 | 27 | 3060 | 5740 | 32400 | 28 | 1400 | 2800 | 36000 | 29 | 20 | 44 | 64 | 29 |
| Cymric | Anderson | NA | NA | NA | 0 | ----- | ----- | 29000 | 1 | ----- | ----- | 13000 | 1 | ----- | ----- | 210 | 1 |
| | Ball | NA | NA | NA | 0 | ----- | ----- | 20000 | 1 | ---- | ----- | 11000 | 1 | ----- | ----- | 91 | 1 |
| | Bowles | NA | NA | NA | 0 | ----- | ----- | 17000 | 1 | ----- | ----- | 7600 | 1 | ----- | ----- | 90 | 1 |
| | Clifford Trust | 22000 | 27000 | 32000 | 2 | ----- | ----- | 11000 | 1 | 5300 | 6800 | 11000 | 3 | 56 | 70 | 92 | 3 |
| | Fee | NA | NA | NA | 0 | ----- | ----- | 21000 | 1 | ----- | ----- | 9400 | 1 | ----- | ----- | 100 | 1 |
| | Lehi-Richardson | 31000 | 35300 | 36000 | 7 | 19000 | 22000 | 22000 | 7 | 10000 | 12000 | 15000 | 7 | 82 | 88 | 120 | 7 |
| | McKittrick 1&1-3 | 14600 | 23500 | 58000 | 58 | 7554 | 14000 | 34800 | 67 | 3228 | 7000 | 18000 | 68 | 48 | 64 | 110 | 58 |
| | McKittrick 1-1 | 15000 | 19000 | 48300 | 9 | 7238 | 12000 | 23000 | 6 | 3664 | 5540 | 16000 | 9 | 29.7 | 62 | 132 | 9 |
| | McKittrick 6, 6A, 6B | 13000 | 13500 | 14000 | 2 | 7700 | 8200 | 8700 | 2 | 3400 | 3650 | 3900 | 2 | 65 | 67 | 69 | 2 |
| | Overland Anderson | NA | NA | NA | 0 | ----- | ----- | 18000 | 1 | ----- | ----- | 8400 | 1 | ----- | ----- | 87 | 1 |
| | Richardson | NA | NA | NA | 0 | ----- | ----- | 18000 | 1 | ----- | ----- | 6900 | 1 | ----- | ----- | 47 | 1 |
| | Roco | NA | NA | NA | 0 | ----- | ----- | 22000 | 1 | ----- | ----- | 12000 | 1 | ----- | ----- | 150 | 1 |
| | Temblor | NA | NA | NA | 0 | ----- | ----- | 22000 | 1 | ----- | ----- | 9200 | 1 | ----- | ----- | 50 | 1 |
| | USL | 34000 | 37250 | 39000 | 6 | 18000 | 23500 | 24000 | 6 | 11000 | 13000 | 14000 | 6 | 87 | 92 | 120 | 6 |
| Devils Den | Fee (A&B) | 23000 | 26500 | 30000 | 4 | 14000 | 16500 | 20000 | 6 | 5500 | 7400 | 9300 | 6 | 6.0 | 16 | 25 | 6 |
| | GraceCairns | ----- | ----- | 13000 | 1 | ----- | ----- | 6500 | 1 | ----- | ----- | 3800 | 1 | ----- | ----- | 1.2 | 1 |
| | Lebaron | ----- | ----- | 23000 | 1 | ----- | ----- | 13000 | 1 | ----- | ----- | 6200 | 1 | ----- | ----- | 2.5 | 1 |
| Lost Hills | Galbreath | ----- | ----- | 42000 | 1 | ----- | ----- | 30000 | 1 | ----- | ----- | 16600 | 1 | ----- | ----- | 143 | 1 |

PSE

Number of samples, minimum, median, and maximum values of electrical conductivity, total dissolved solids, chloride, and boron for each facility provided in Supporting Information

# BTEX Detection Facility Summary

| Field | Lease | Benzene minimum (µg/L) | Benzene maximum (µg/L) | Detections/ Analyses | Toluene minimum (µg/L) | Toluene maximum (µg/L) | Detections/ Analyses | Ethylbenzene minimum (µg/L) | Ethylbenzene maximum (µg/L) | Detections/ Analyses | Total Xylene minimum (µg/L) | Total Xylenes maximum (µg/L) | Detections/ Analyses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **North-Eastern Kern Subbasin** | | | | | | | | | | | | | |
| Jasmin | Davies Realty | ----- | <0.08 | 0/1 | ----- | <0.09 | 0/1 | ----- | <0.09 | 0/1 | ----- | <0.36 | 0/1 |
| Jasmin | Quinn | <0.08 | <10 | 0/25 | <0.09 | 13 | 8/25 | <0.50 | 13 | 4/25 | <0.50 | 95 | 12/25 |
| Kern Front | No. 2 Treatment | <0.37 | <2.0 | 0/24 | <0.31 | 7.5 | 1/24 | <0.50 | <2.0 | 0/24 | <0.50 | <2.0 | 0/22 |
| | Pedro USL | ----- | <2.5 | 0/1 | ----- | <2.5 | 0/1 | ----- | <2.5 | 0/1 | ----- | <2.5 | 0/1 |
| | Signal | ----- | <5.0 | 0/1 | ----- | <5.0 | 0/1 | ----- | <5.0 | 0/1 | ----- | <5.0 | 0/1 |
| Kern River | Beardsley and Carrier | <1.0 | <2.0 | 0/2 | <0.5 | <2.0 | 0/2 | <0.5 | <2.0 | 0/2 | <1.0 | <4.0 | 0/2 |
| Mount Poso | Jones | ----- | <0.50 | 0/1 | ----- | <0.50 | 0/1 | ----- | <0.50 | 0/1 | ----- | <0.50 | 0/1 |
| Poso Creek | Desert Glow | <2.0 | <10 | 0/2 | <2.0 | 200 | 1/2 | <2.0 | <10 | 0/2 | <2.0 | <10 | 0/2 |
| | Government | ----- | <5.0 | 0/1 | ----- | 20.9 | 1/1 | ----- | <5.0 | 0/1 | ----- | 29.6 | 1/1 |
| | McVan | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 |
| **Central-Eastern Kern Subbasin** | | | | | | | | | | | | | |
| Edison | Claflin | ----- | 0.55 | 1/1 | ----- | <0.50 | 0/1 | ----- | <0.50 | 0/1 | ----- | 2.6 | 1/1 |
| | Fee 34 | 1.6 | 2410 | 12/16 | <0.50 | 2210 | 11/16 | <0. | 213 | 7/16 | <0.50 | 1110 | 14/16 |
| | Lehr | 0.52 | <5.0 | 1/2 | <0.09 | <5.0 | 0/2 | <0.09 | <5.0 | 0/2 | <0.36 | <0.50 | 0/2 |
| | Racetrack | <0.08 | 0.37 | 1/4 | <0.09 | <0.27 | 0/4 | <0.09 | 0.54 | 1/4 | ----- | 6.1 | 1/4 |
| | Race Track Hill | <0.50 | 320 | 6/17 | <0.50 | 210 | 6/17 | <0.50 | 2.0 | 1/17 | <0.50 | 246 | 7/17 |
| **Western Kern Subbasin** | | | | | | | | | | | | | |
| Asphalto | CA Federal A | ----- | 1400 | 1/1 | ----- | 1300 | 1/1 | ----- | 90 | 1/1 | ----- | 660 | 1/1 |
| | Ferguson | ----- | 1800 | 1/1 | ----- | 1400 | 1/1 | ----- | 85 | 1/1 | ----- | 600 | 1/1 |
| | Standard | 4050 | 5700 | 2/2 | 5600 | 5990 | 2/2 | 310 | 356 | 2/2 | 2160 | 2770 | 2/2 |
| Carneros Creek | Anderson | 57.8 | 1340 | 2/2 | 10.2 | 4780 | 2/2 | <5.0 | 512 | 1/2 | 183 | 2170 | 2/2 |
| | Standard | ----- | <5.0 | 0/1 | ----- | 5.51 | 1/1 | ----- | <5.0 | 0/1 | ----- | 5.17 | 1/1 |
| | Santa Fe Energy | 780 | 1340 | 2/2 | 875 | 4780 | 2/2 | 86.7 | 512 | 2/2 | 334 | 2170 | 2/2 |
| | Theta (30) | ----- | 323 | 1/1 | ----- | 348 | 1/1 | ----- | 90.5 | 1/1 | ----- | 334 | 1/1 |
| Chico-Martinez | Mitchel | <1.0 | <10.0 | 4/23 | <2.0 | 13.2 | 9/232 | <1.0 | <10.0 | 8/23 | 2.2 | 34 | 18/23 |
| Cymric | Anderson | ----- | 200 | 1/1 | ----- | <10 | 0/1 | ----- | 31 | 1/1 | ----- | 23 | 1/1 |
| | Ball | ----- | <10 | 0/1 | ----- | <10 | 0/1 | ----- | <10 | 0/1 | ----- | <10 | 0/1 |
| | Bowles | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 | ----- | 2.2 | 1/1 | ----- | 13 | 1/1 |
| | Clifford Trust | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 |
| | Fee | ----- | 7.6 | 1/1 | ----- | 5.7 | 1/1 | ----- | 5.8 | 1/1 | ----- | 32 | 1/1 |
| | Lehi-Richardson | ----- | <5.0 | 0/3 | ----- | <5.0 | 0/3 | ----- | <5.0 | 0/3 | ----- | <? | 0/3 |
| | McKittrick 1&1-3 | <0.25 | 1500 | 35/57 | 0.31 | 1600 | 45/57 | <0.25 | 120 | 29/57 | 1.2 | 640 | 42/57 |
| | McKittrick 1-1 | <0.50 | 1100 | 4/5 | <0.50 | 1300 | 4/5 | <0.50 | 100 | 3/5 | <0.50 | 650 | 3/5 |
| | McKittrick 6, 6A, 6B | 0.82 | 44 | 2/2 | 4.0 | 330 | 2/2 | <0.5 | 25 | 1/2 | 3.0 | 62 | 2/2 |
| | Overland Anderson | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 | ----- | 2.2 | 1/1 | ----- | 14 | 1/1 |
| | Richardson | ----- | <10 | 0/1 | ----- | <10 | 0/1 | ----- | <10 | 0/1 | ----- | <10 | 0/1 |
| | Roco | ----- | <10 | 0/1 | ----- | <10 | 0/1 | ----- | <10 | 0/1 | ----- | <10 | 0/1 |
| | Temblor | ----- | 35 | 1/1 | ----- | <2.0 | 0/1 | ----- | <2.0 | 0/1 | ----- | 6.0 | 1/1 |
| | USL | <5.0 | <5.0 | 0/2 | <5.0 | <5.0 | 0/2 | <5.0 | <5.0 | 0/2 | <5.0 | <5.0 | 0/2 |
| Devils Den | Fee (A&B) | <0.08 | <0.42 | 0/2 | <0.09 | <0.46 | 0/2 | <0.09 | <0.49 | 0/2 | <0.36 | <1.8 | 0/2 |

Number of samples, detection frequency, minimum, and maximum values of benzene, toluene, ethylbenzene, and xylenes at each facility provided in Supporting Information. Low number of detections and variable MDLs for BTEX compounds precluded computation of median values.

# TDS Levels in Groundwater in Tulare Basin

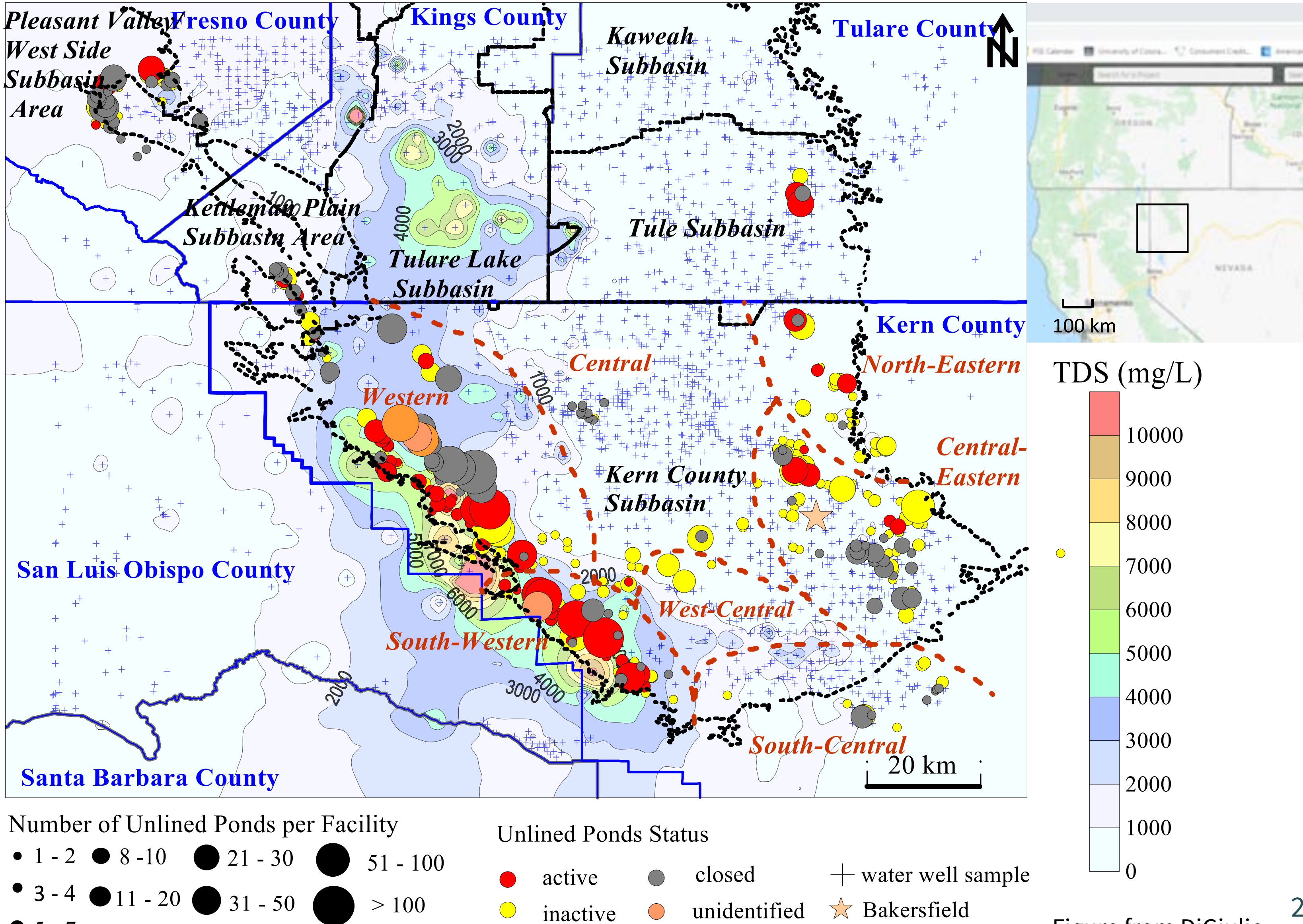
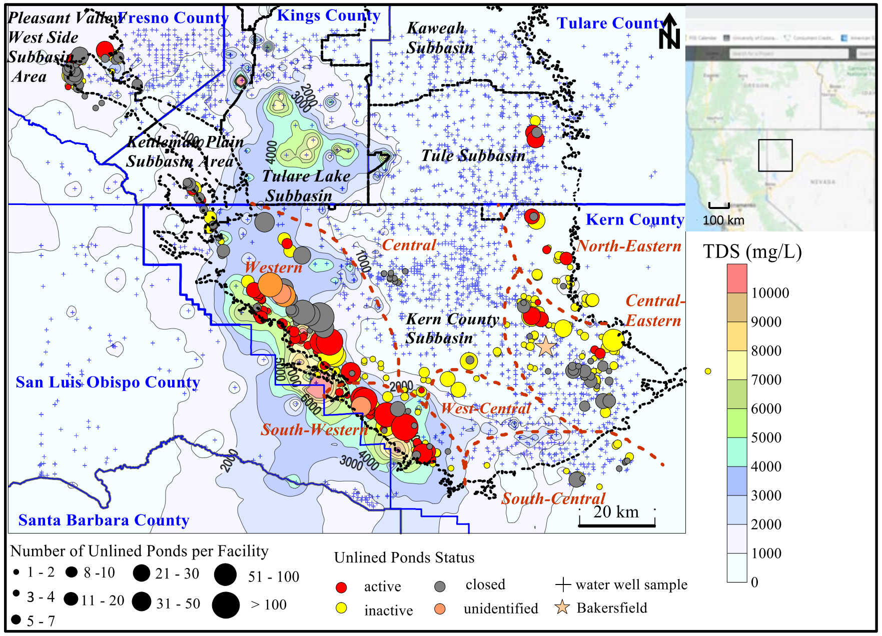
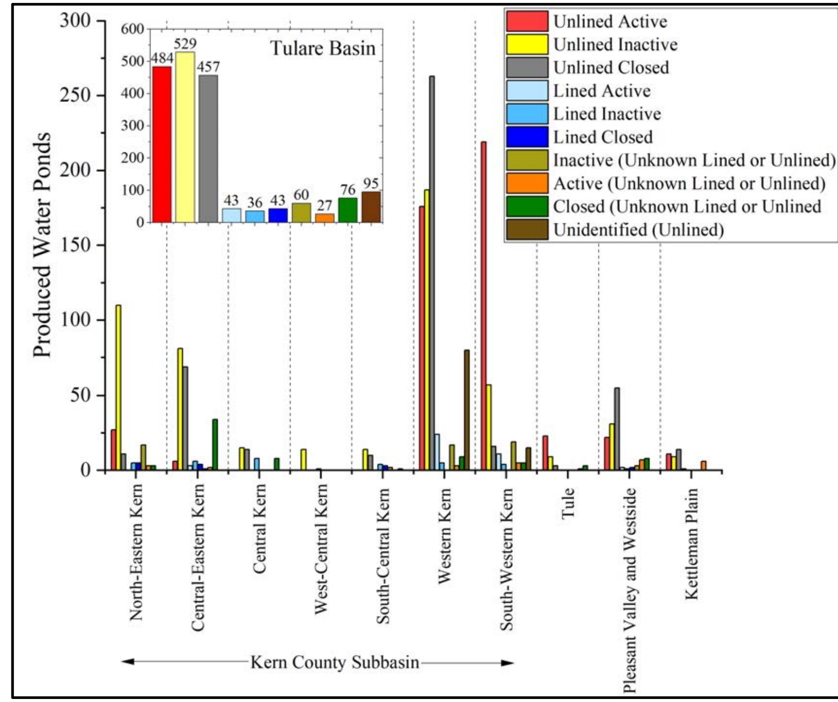
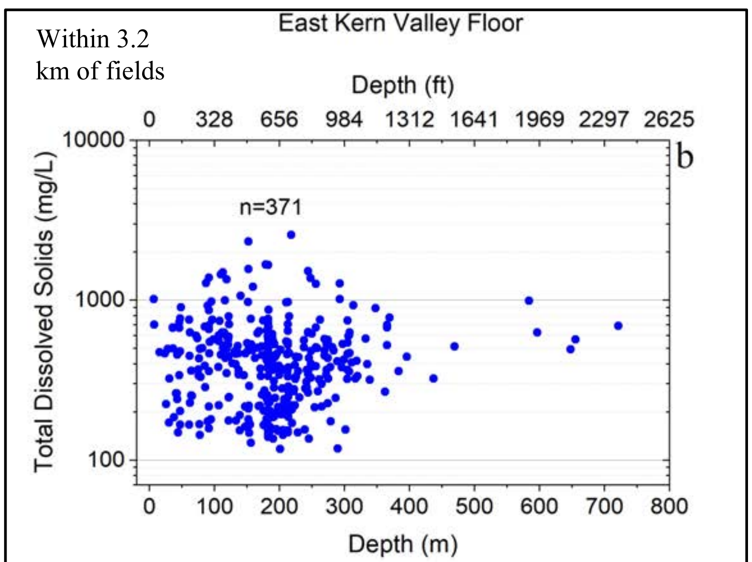



Figure from DiGiulio et al. (2021) (ES&T).

# Central–Eastern Kern County Subbasin




Figures from DiGiulio et al. (2021) (ES&T)

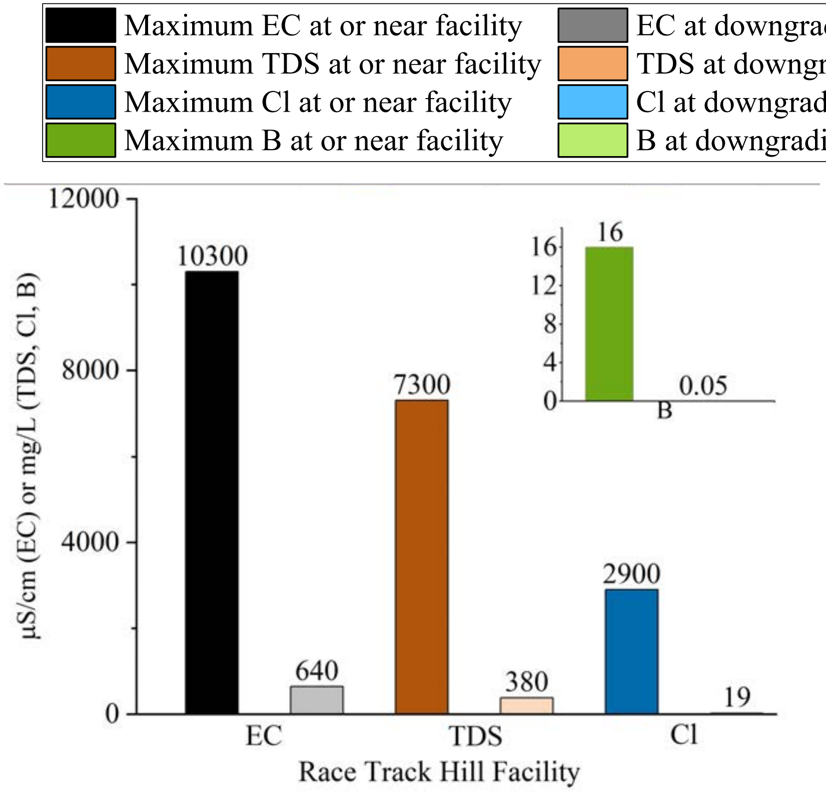
206 ponds of which 156 are unlined of which 6 are still active.

TDS levels in groundwater are generally <1000 mg/L to a depth ~ 700 m.

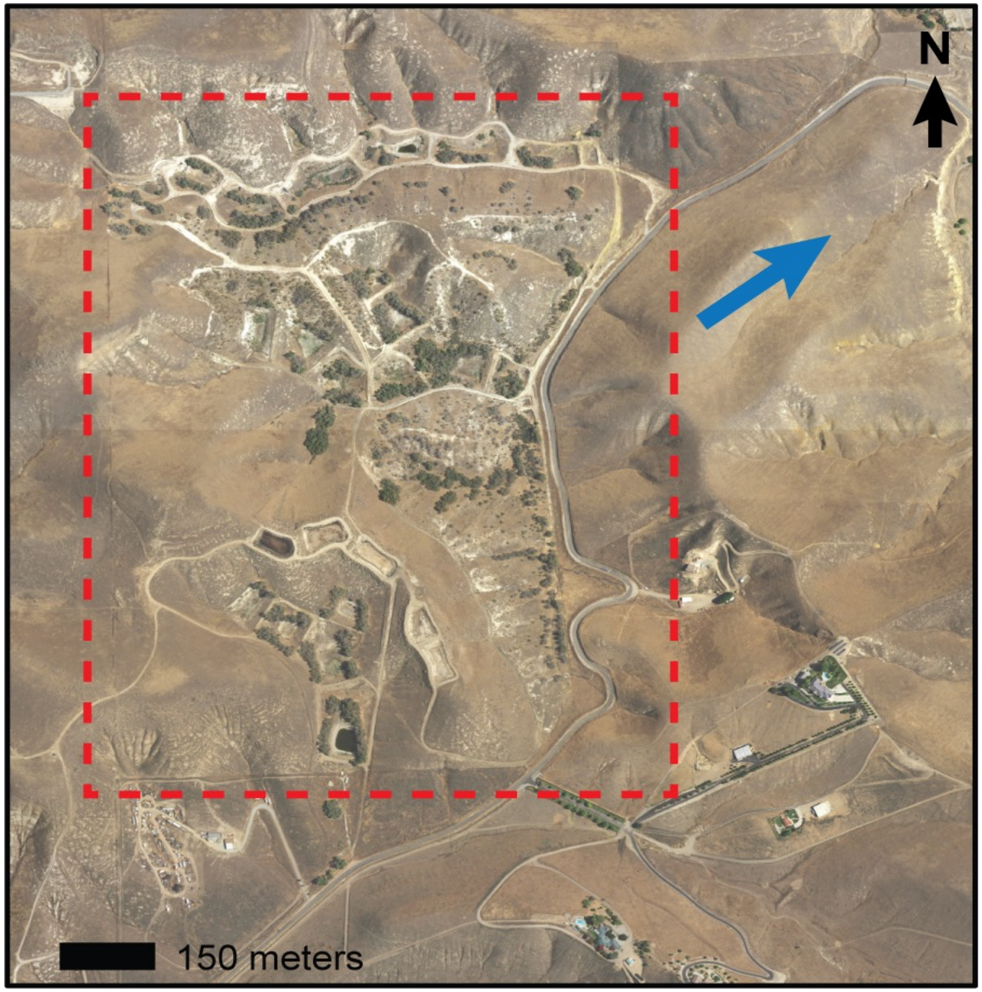
**Effluent Limit (EC: 1000 µS/cm, Cl: 200 mg/L, B: 1.0 mg/L)**

| | Medians | Maximums |
|---|---|---|
| EC (µS/cm) | 740-6500 | 9800 |
| TDS (mg/L) | 515-3670 | 6600 |
| Chloride (mg/L) | 29-2010 | 3300 |
| Boron (mg/L) | 0.51-14 | 240 |
| Benzene (µg/L) | | 2410 |
| Toluene (µg/L) | | 2210 |
| Ethylbenzene (µg/L) | | 213 |
| Xylenes (µg/L) | | 1110 |

# Race Track Hill Facility



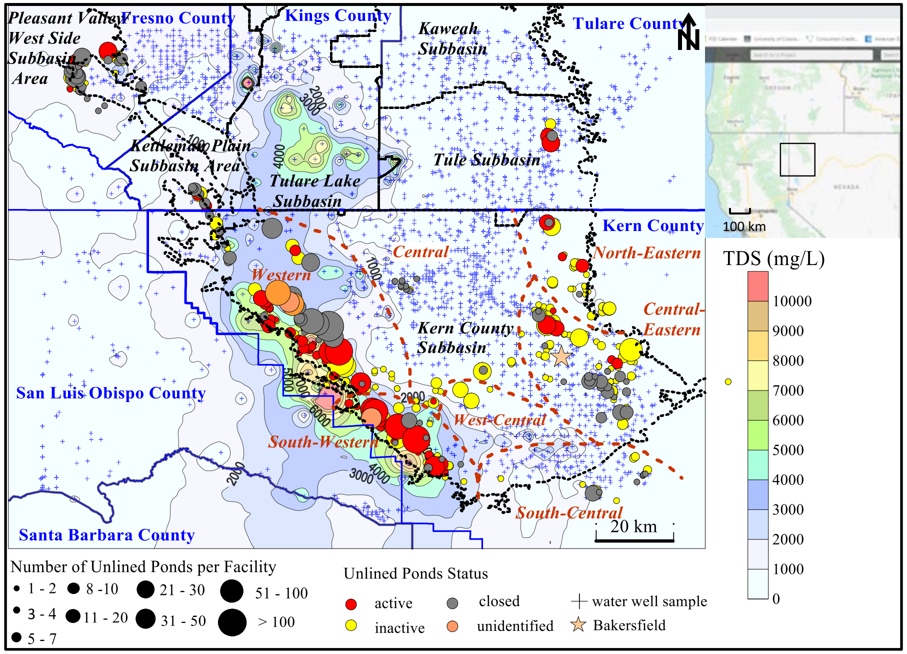

Figures from DiGiulio et al. (2021) (ES&T).

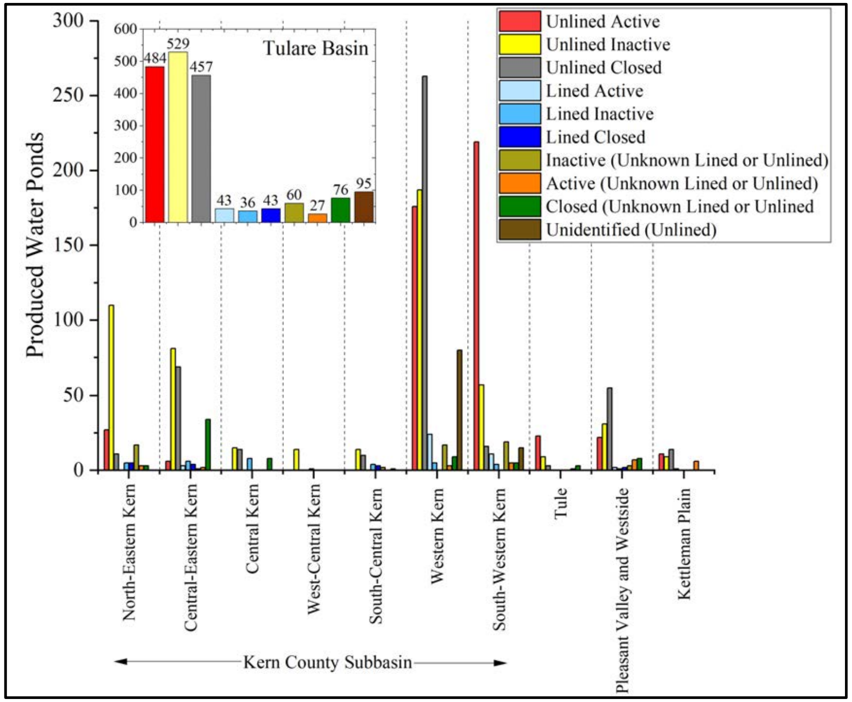


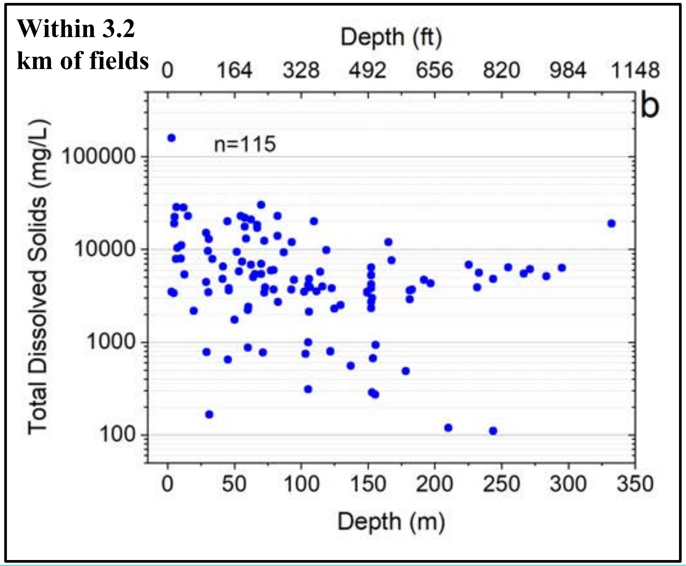

The inactive **Race Track Hill Facility** near the Edison Field consists of 27 unlined ponds, was in operation since 1960 and received ~3.7 MMbbls/yr.

Elevated levels of EC, TDS, Cl, and B in Kern River Formation within and at the boundary of the facility and a lower levels at an unimpacted well ~0.5 km northeast of the facility. Monitoring wells not present between facility boundary and unimpacted monitoring well.

# Western Kern County Subbasin




Figures from DiGiulio et al. (2021) (ES&T).

764 ponds of which 626 are unlined of which 176 are still active.

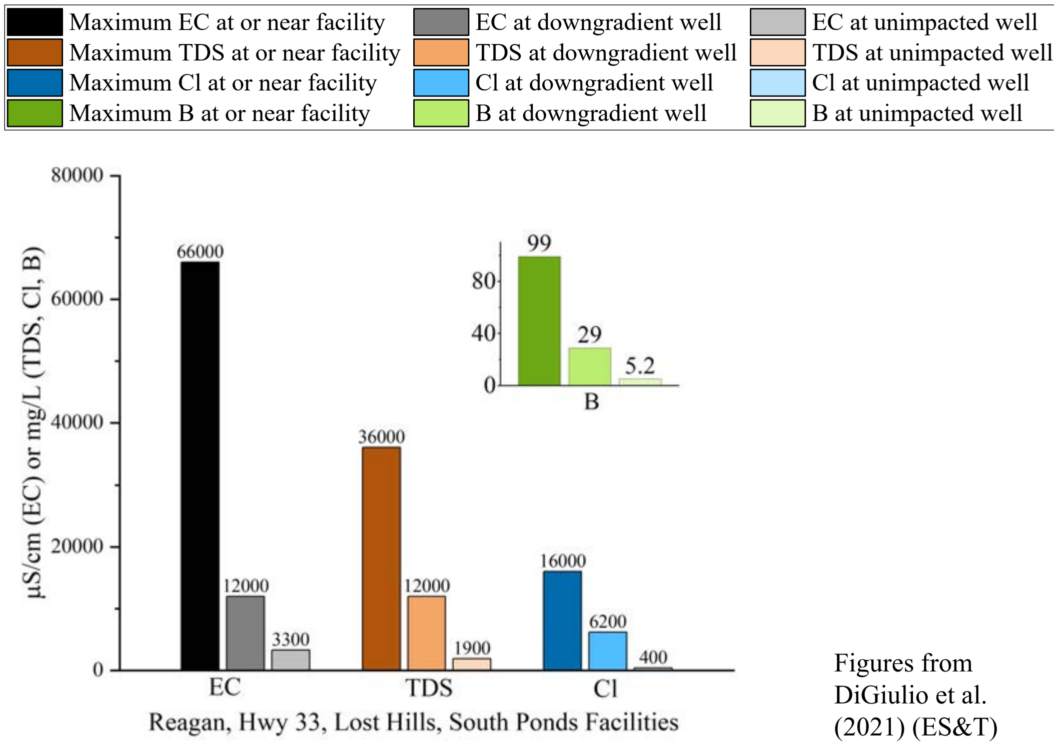
In the western area, TDS <1000 to over 10,000 mg/L with ~350 m.

Most ponds lie directly east of oil fields where this is a transition to fresher (TDS 3,000 – 4,000 mg/L) groundwater toward the synclinal axis of the valley.

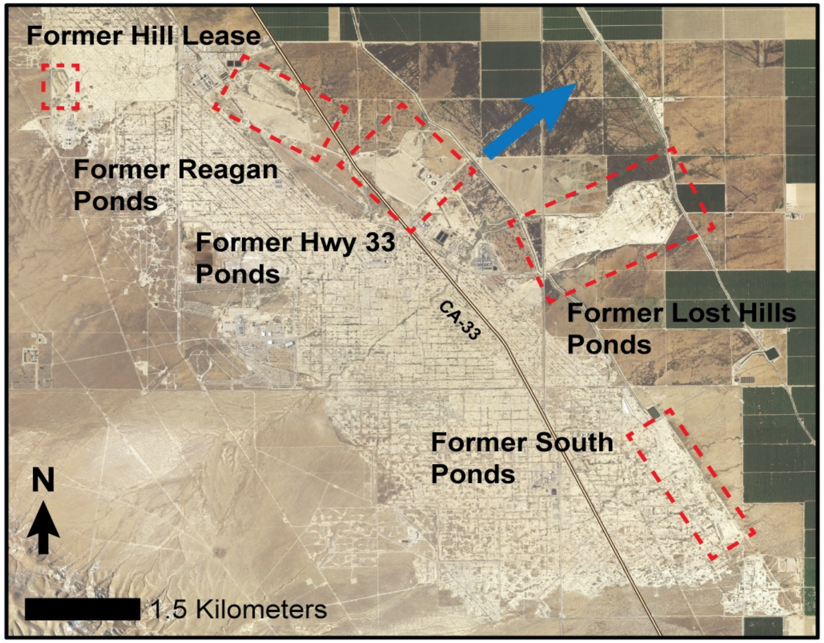
**Effluent Limits (EC: 1000 µS/cm, Cl: 200 mg/L, B: 1.0 mg/L)**

| | Medians | Maximums |
|---|---|---|
| EC (µS/cm) | 4200-70500 | 72000 |
| TDS (mg/L) | 3635-41000 | 42000 |
| Chloride (mg/L) | 150-24000 | 36000 |
| Boron (mg/L) | 1.9-260 | 290 |
| Benzene (µg/L) | | 5700 |
| Toluene (µg/L) | | 5990 |
| Ethylbenzene (µg/L) | | 4000 |
| Xylenes (µg/L) | | 20700 |

# Reagan, Hwy 33, Lost Hills, and South Ponds Facilities




Figures from DiGiulio et al. (2021) (ES&T)




Facilities located east of the Belridge South Field, in operation between the early 1960s to 2006-2008.

The Former Reagan Ponds Facility had 32 unlined ponds and received ~32 MMbbls/yr.

The Former Hwy 33 Ponds Facility had 28 unlined ponds and received ~40 MMbbls/yr.

The former Lost Hills Ponds Facility had 107 ponds and received ~34 MMbbls/yr.

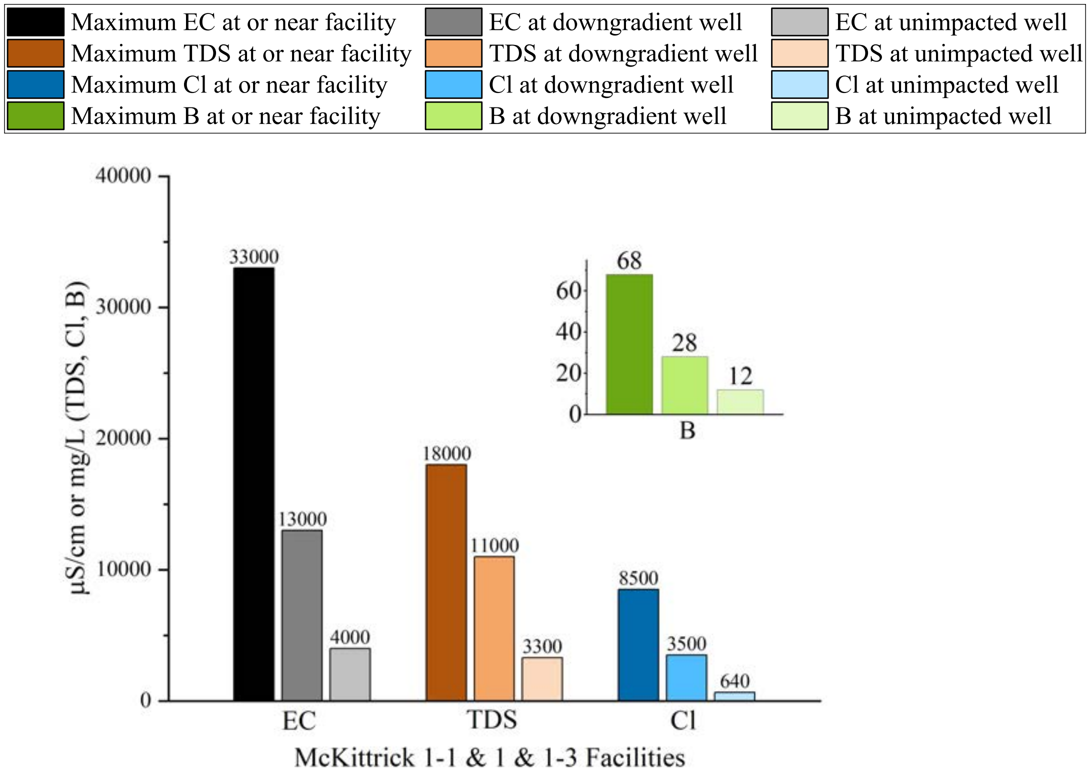
The Former South Ponds Facility had 18 unlined ponds and received ~18 MMbbls/yr.

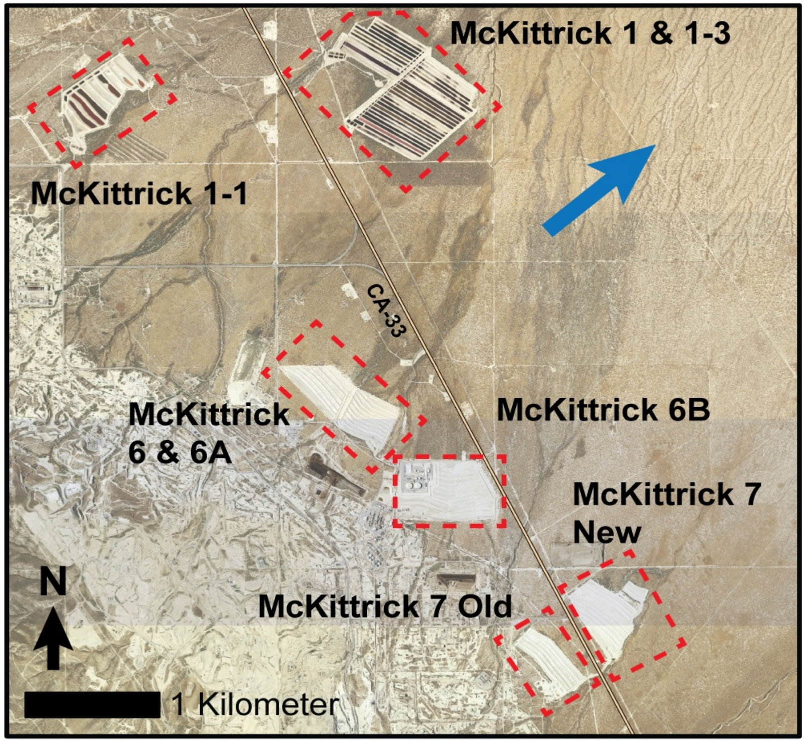
In this area, alluvium is underlain by the 22K Sand. Elevated levels of EC, TDS, Cl, and B in 22K Sand ~4 km northeast of facility. Unimpacted well ~6 km northeast of the facility.

Based on estimates of disposal within 12 months of closure, cumulatively over 6 billion barrels of produced water was disposed in unlined ponds over a 50-year period in this area.

Active remediation deemed too expensive ($1,500,000,000) at the South Ponds and Lost Hills Facilities so monitored natural attenuation chosen ($1,300,000) chosen to address contamination.

# McKittrick 1-1 and 1 & 1-3 Facilities




Figures from DiGiulio et al. (2021) (ES&T)

The active **McKittrick 1-1** and **1 & 1-3 Facilities** located east of the Cymric Field have been in operation between the early 1960s.

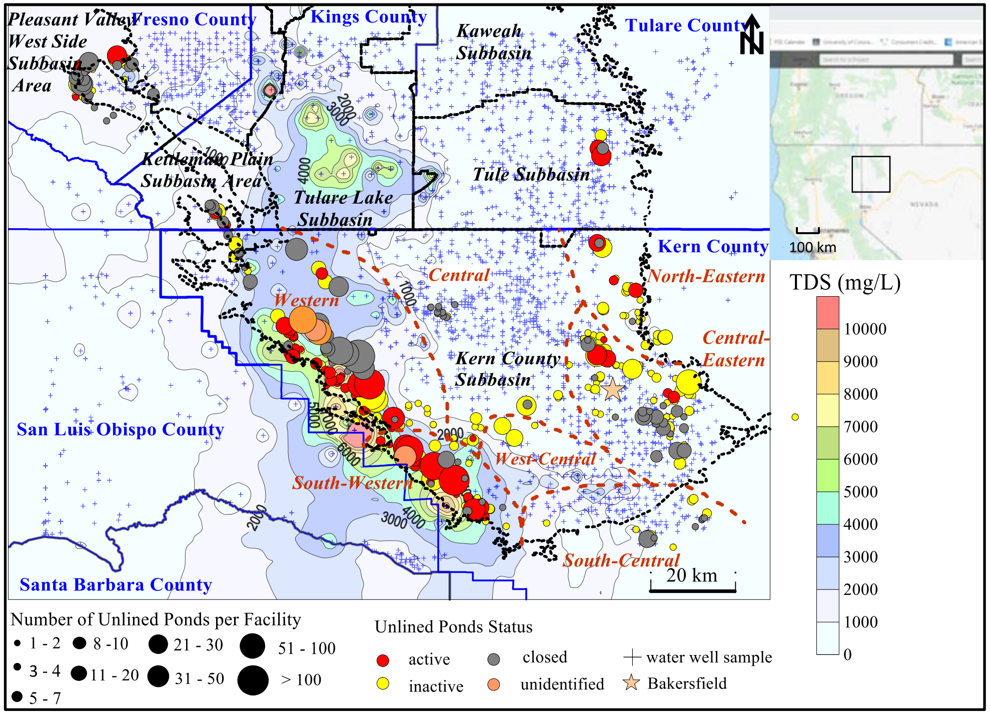
The McKittrick 1-1 Facility consists of 23 unlined ponds and receives ~13 MMbbls/yr.

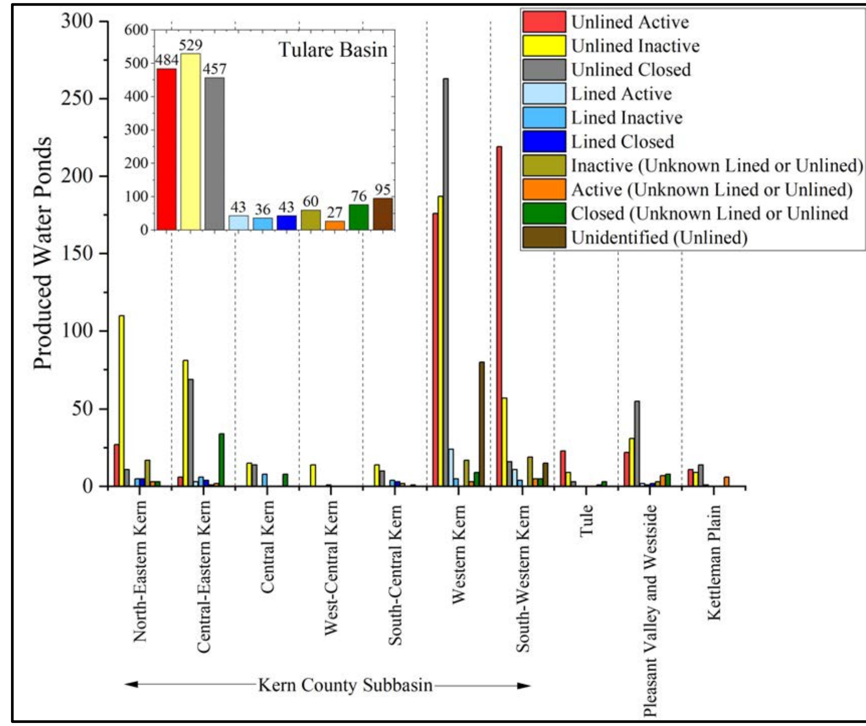
The McKittrick 1&1-3 Facility consists of 62 unlined ponds and receives ~25 MMbbls/yr.

In the vicinity of the facility, produced water has saturated the Upper Tulare Formation present beneath alluvium and the Corcoran Clay Equivalent and contaminated the Lower Tulare Formation – the regional aquifer. Groundwater in alluvium and the Upper Tulare Formation transition from variably saturated media to regional aquifers east-northeast of the facility.

Elevated levels of EC, TDS, Cl, and B detected in the Lower Tulare Formation ~ 2 km northeast of facilities. Unimpacted monitoring well in Lower Tulare Formation ~3 km further northeast of the facility.

# South-Western Kern County Subbasin



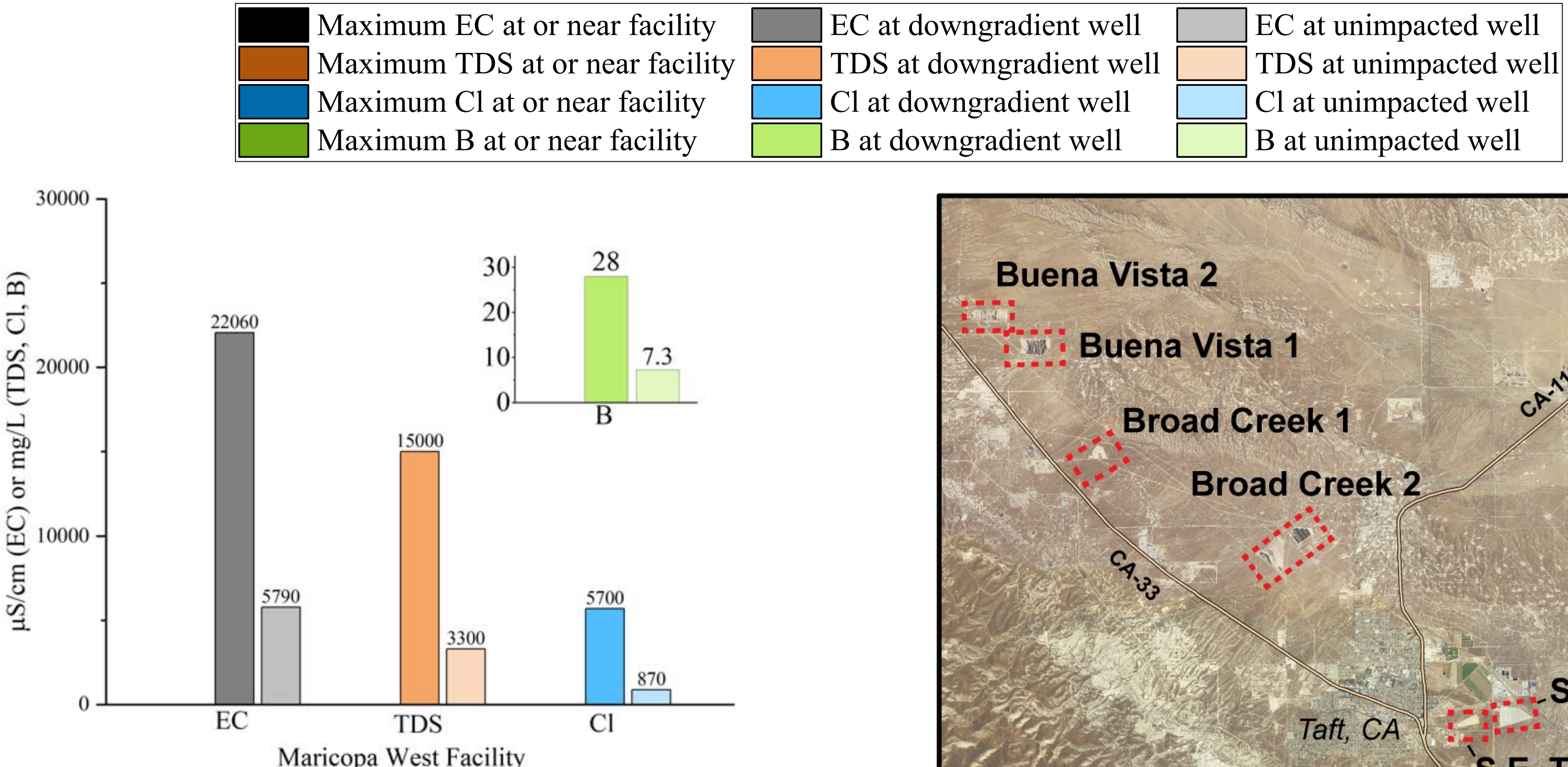



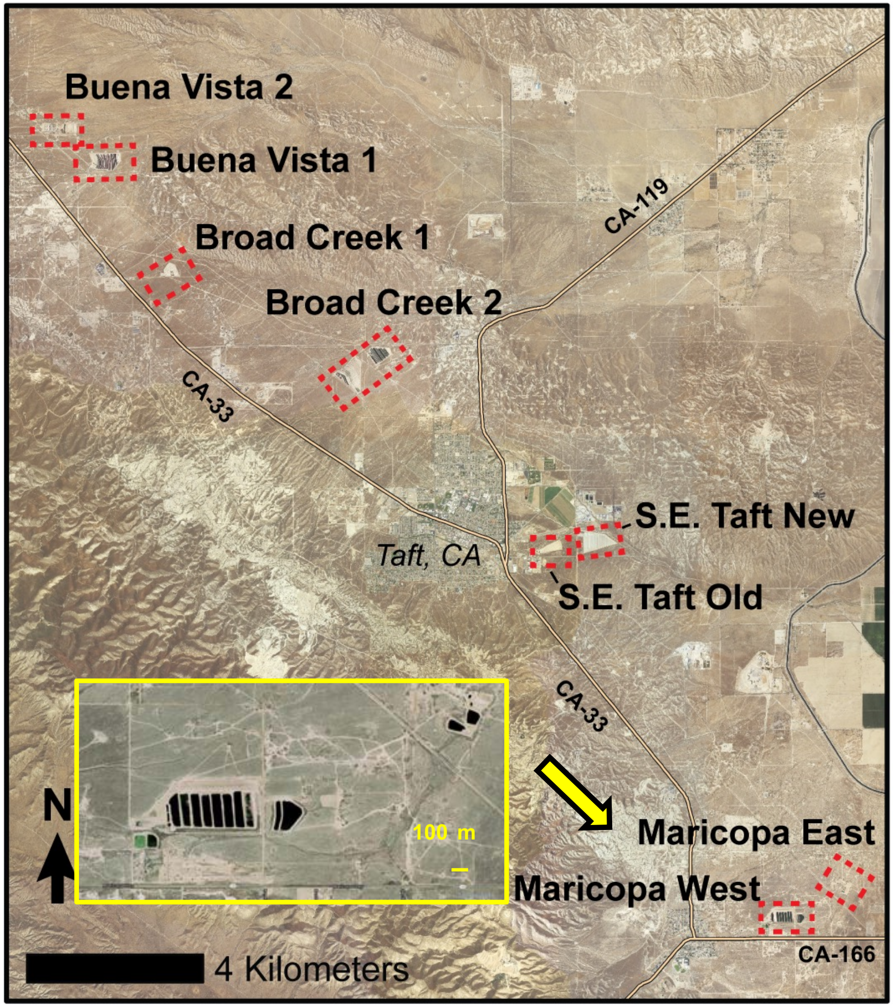

Contains the Buena Vista and Midway-Sunset Fields.

351 ponds of which 292 are unlined of which 219 are still active.

| | Medians | Maximums |
|---|---|---|
| EC (µS/cm) | 5180-48000 | 215585 |
| TDS (mg/L) | 3400-32200 | 94984 |
| Chloride (mg/L) | 1100-20000 | 59600 |
| Boron (mg/L) | 24-123 | 360 |
| Benzene (µg/L) | | 3600 |
| Toluene (µg/L) | | 4600 |
| Ethylbenzene (µg/L) | | 730 |
| Xylenes (µg/L) | | 3060 |

# Maricopa Facilities




The **Maricopa West Facility** has been in operation since 1961 and consists of 13 unlined ponds that receive ~6.2 MMbbls/yr.

The **Maricopa East Facility** consists of 7 unlined ponds. No information on effluent composition. No groundwater monitoring.

Elevated levels of EC, TDS, Cl, and B in alluvium ~1.2 km east of Maricopa West Facility. Unimpacted well ~2.1 km east of the facility. No monitoring wells in immediate vicinity of facility.

# Implications of Investigation

# The Potential for Groundwater Impact is High

The disposal of produced water into unlined produced water ponds has been occurring since the early 1900s and continues to this day.

Produced water often has high levels of electrical conductivity, total dissolved solids, chloride, boron, and volatile organic compounds, such as benzene, which are mobile in groundwater.

Disposal of produced water into unlined ponds often overlies groundwater having present and future potential use.

Groundwater monitoring is sparse, but where monitoring has occurred, impact to groundwater resources has been observed and proven too expensive to actively remediate.



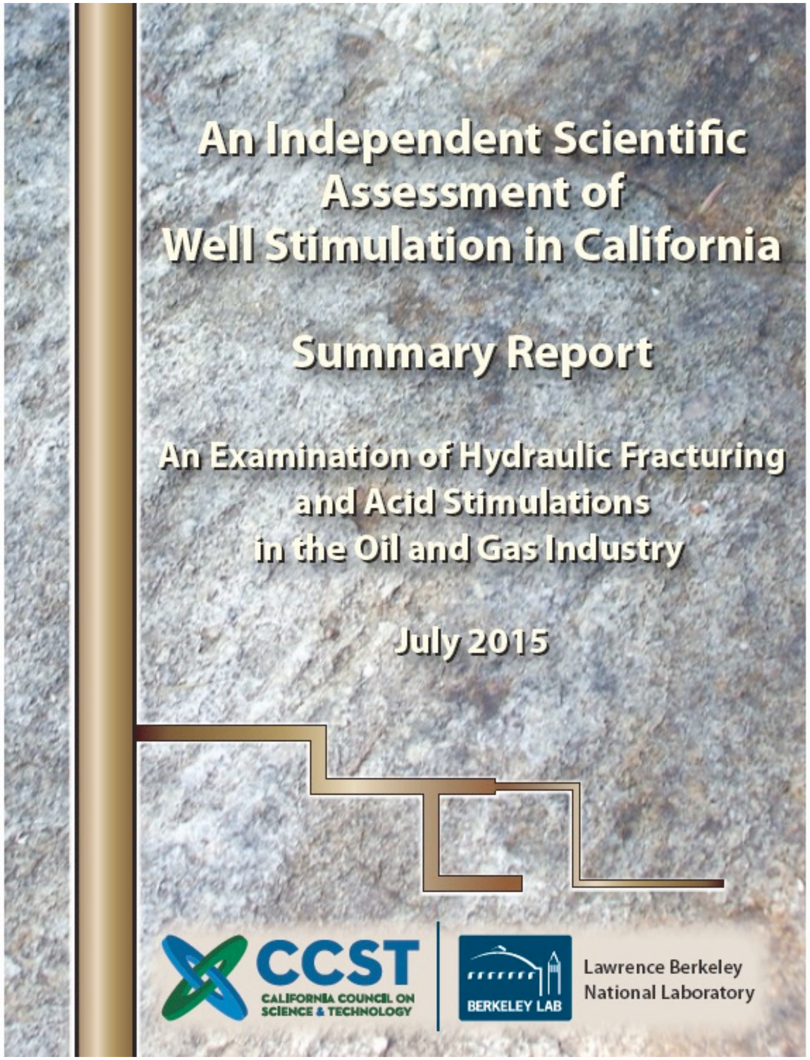
PSE

# Disposal Practice Should Be Better Regulated

In January 2015, in an independent scientific study conducted pursuant to CA Senate Bill 4 and commissioned by the CA Natural Resources Agency on well stimulation in California, the CA Council on Science & Technology and the Lawrence Berkeley National Laboratory concluded that the disposal of produced water in unlined ponds poses a risk to groundwater resources in California and that produced water discharged to unlined produced water ponds should contain non-hazardous concentrations of chemicals or their use should be phased out in the future.

They stated further that groundwater investigations should be conducted to determine if historical disposal activities have impacted groundwater resources in the vicinity of these ponds.

Results of our comprehensive assessment of unlined ponds bolsters these recommendations.




PSE

# Better Regulation with Consistent Definition of Protected Groundwater

| Maximum TDS (mg/L) | Applicability to O&G Industry | Enforceability | Overseeing Agencies |
|---|---|---|---|
| **3,000 mg/L or EC < 5,000 µS/cm for municipal water supply (MUN)** | Land disposal, produced water ponds | *States Sources of Drinking Water Policy* (SWRCB Res No. 88-63 (SWRCB 2006). TDS and EC not defined for other beneficial use such as that used for agriculture (AGR). | SWRCB |
| **Undefined** | Conventional O&G Development | PRC § 1722.22 for casing requirements | CalGEM |
| **10,000** | Well stimulation | USDW, CA Water Code § 10783(k)(2) | CalGEM, SWRCB |
| **10,000** | UIC Program | UDSW, protected unless exempted, 40 C.F.R. 144.3 | EPA, CalGEM |
| **10,000** | O&G development on federal or tribal land | Onshore Oil & Gas Order No. 2, 53 Federal Register 46798 | BLM, CalGEM, SWRCB |

This investigation supports a recommendation that the definition of protected groundwater during disposal of produced water into unlined produced water ponds should be consistent with the definition of protected groundwater utilized in California's UIC program and for hydraulic fracturing.

This inconsistency appears to be the major driver for this continued disposal practice, especially in the western and south-western portion of the Kern Subbasin or Tulare Basin.

# Thank You

Dominic C. DiGiulio, PhD
Senior Scientist
domdigiuliopsehealthyenergy.org

PSE
Bringing science
to energy policy

Facebook.com/
PSEHealthyEnergy

www.psehealthyenergy.org

@PhySciEng

# Supplemental Slides

# Oil Development in the San Joaquin Valley

Photo Fracktracker.org

The San Joaquin Valley is one of the oldest (1870s) and most productive oil and gas producing basins in the U.S., with more than 100,000 oil and gas wells.



PSE

# Water Use in the San Joaquin Valley

The San Joaquin Valley is one of the most agriculturally productive regions in the world.

The San Joaquin Valley supplies over one-third of the vegetables and two-thirds of the fruits and nuts consumed in the United States.

Agriculture in the San Joaquin Valley is dependent on surface water from winter/spring snowpack melt with excess demand met by groundwater withdrawal especially during drought years.

Photo credit: Richard Thornton/Shutterstock

The San Joaquin Valley also has nearly 4 million residents, most of which rely on groundwater for domestic water supply.



PSE

# Sustained Droughts

The drought and continued groundwater depletion in the San Joaquin Valley has highlighted the need to protect remaining groundwater resources from degradation associated with industrial practices including those associated with oil and gas development.

Photo credit: USGS

The 2012 - 2016 drought was unprecedented at least over the past 1,200 years.

Severity in large part caused by elevated temperatures from climate change and resultant increased evapotranspiration.

There is climatic regime emerging in which all future dry years will coincide with unusually warm years increasing sustained severe droughts.

The drought resulted in substantial groundwater depletion in the Central Valley as measured by water balance methods and Gravity Recovery and Climate Experiment (GRACE) satellite imagery.



PSE

# Increasing Produced Water Production

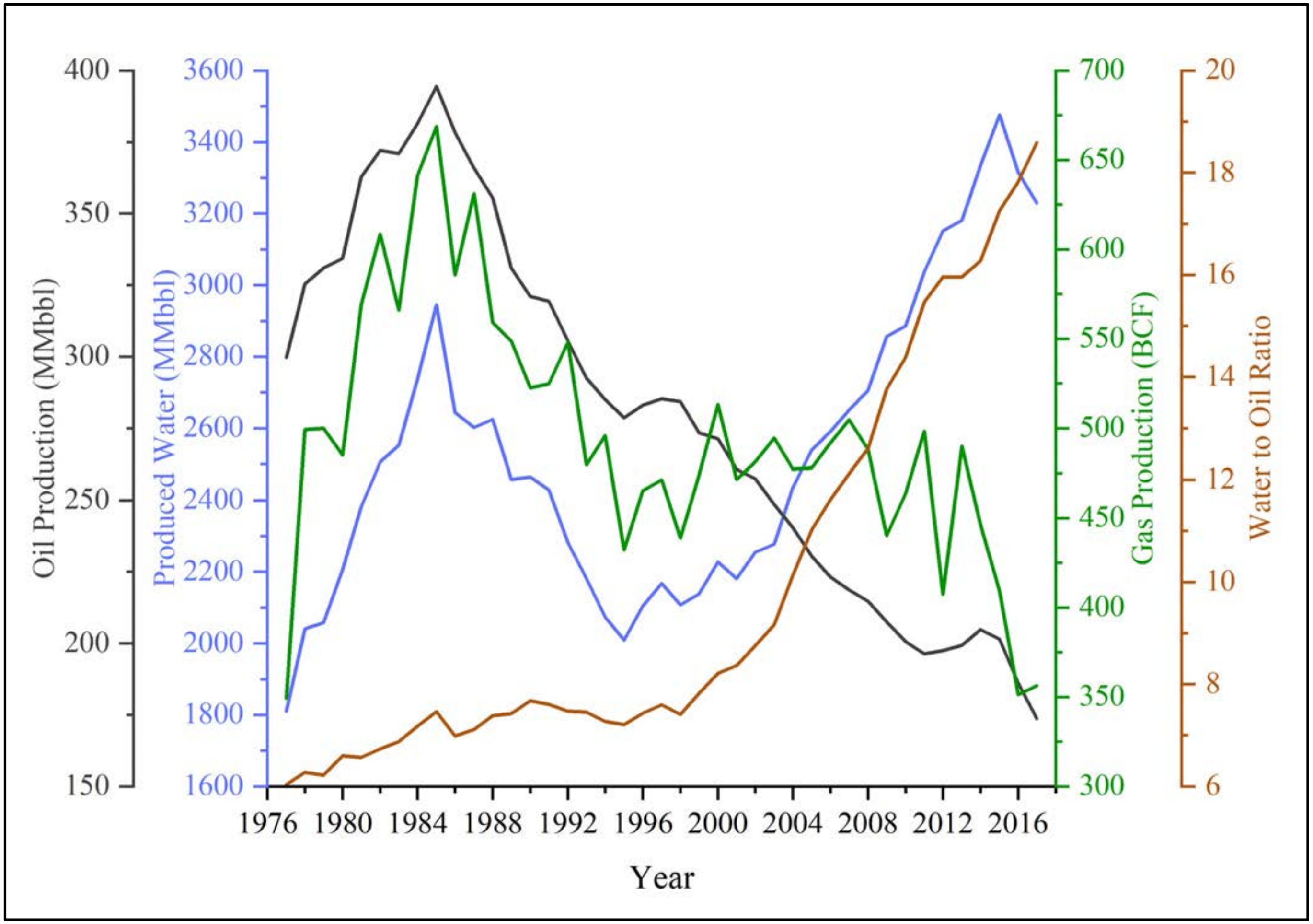



Figure from DiGiulio et al. (2021)

Produced water generation continues to increase in California despite falling oil and natural gas production.

# Disposition with Time for Surface Disposal

Disposal of produced water into unlined produced water ponds decreased precipitously after 2014, corresponding to only 1.4% in 2017 (45 MMbbls) of produced water disposition that year.

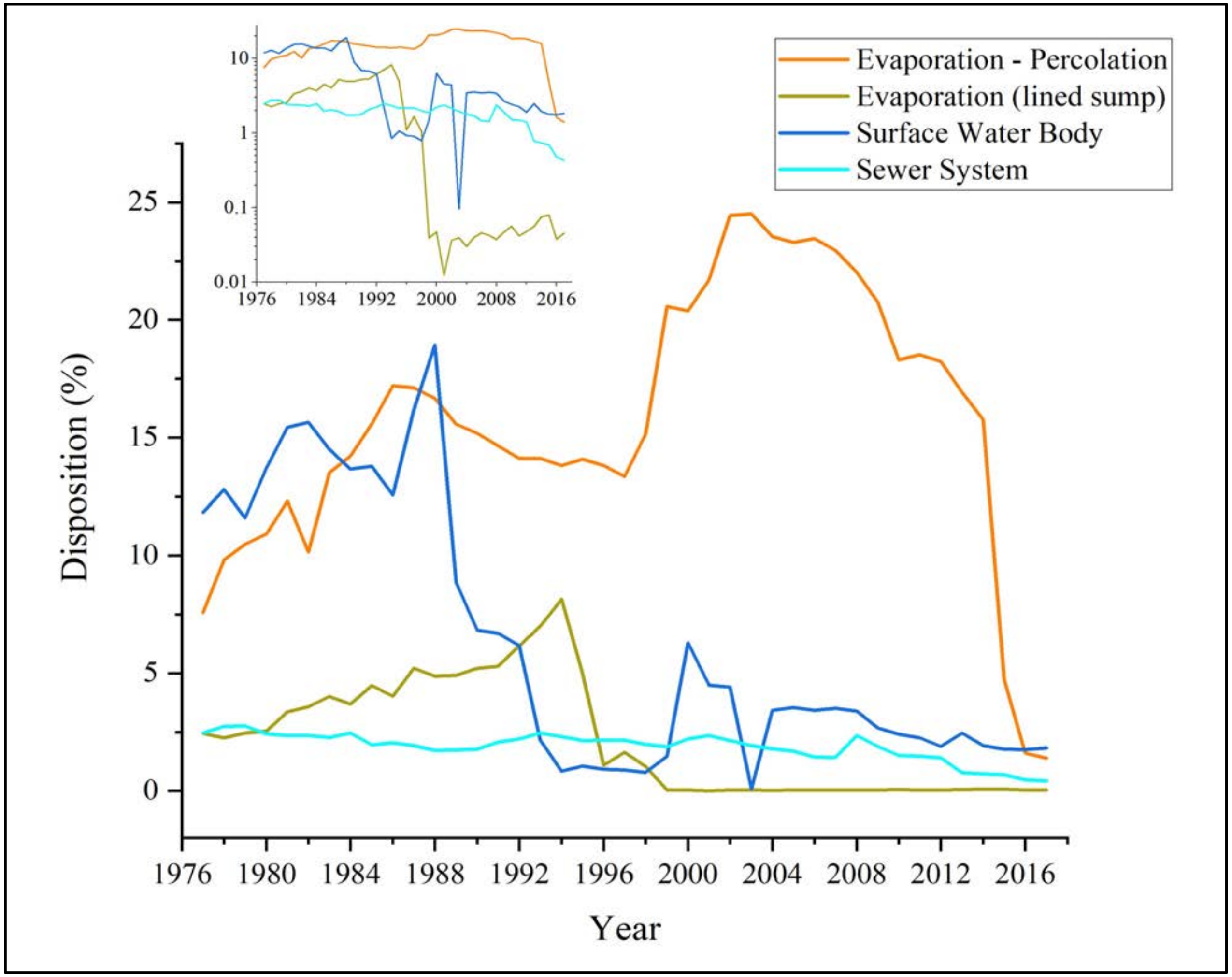
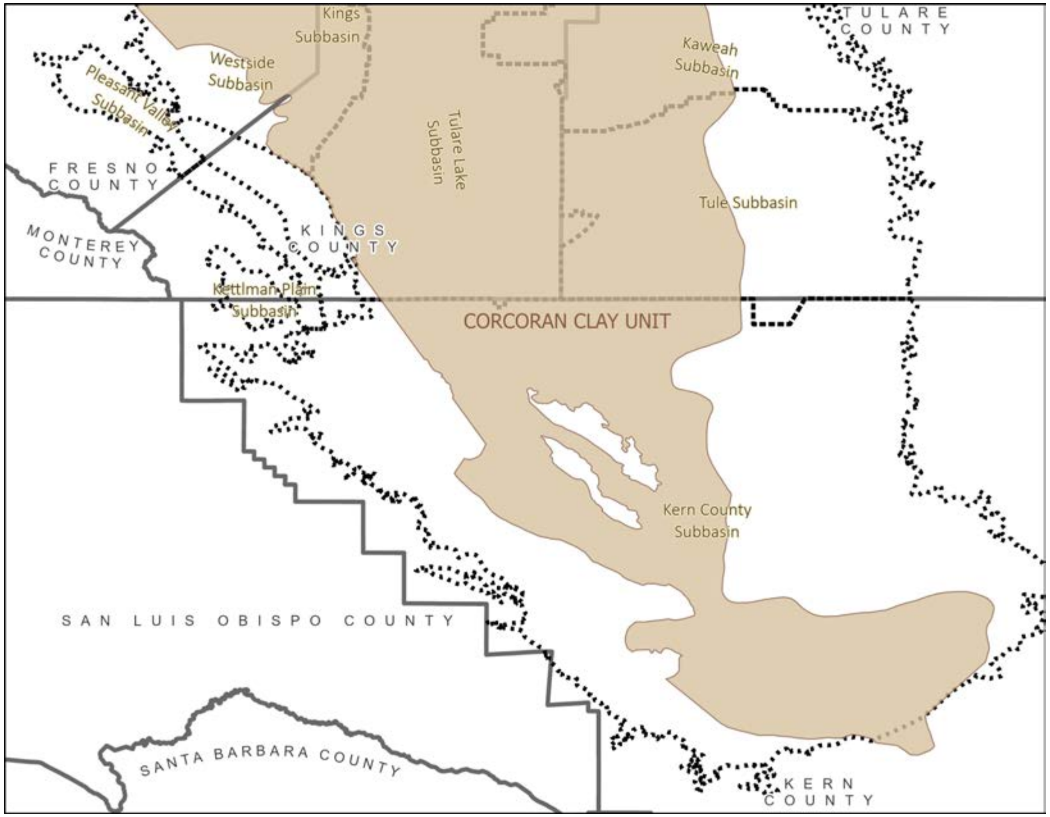



Figure from DiGiulio et al. (2021).

# Corcoran Clay Unit

During Pleistocene time, most of the San Joaquin Valley was inundated by lakes that accumulated up to 60 m of clay often referred to as the Corcoran Clay member of the Tulare Formation now overlying alluvium. Coarser-grained zones are present when the clay is less than 6 m in thickness along the western edge of the unit where many unlined ponds are located. In the central part of the basin, the Corcoran Clay divides the groundwater flow system into an upper unconfined zone in alluvium and a lower confined or semi-confined zone in the Tulare Formation. However, thousands of irrigation wells have perforated the Corcoran Clay and increased the hydraulic connection between these units.




Plot illustrating the extent of Corcoran Clay Unit in the Tulare Basin. Shape file from USGS (1986). Figure from DiGiulio et al. (2021) (ES&T).

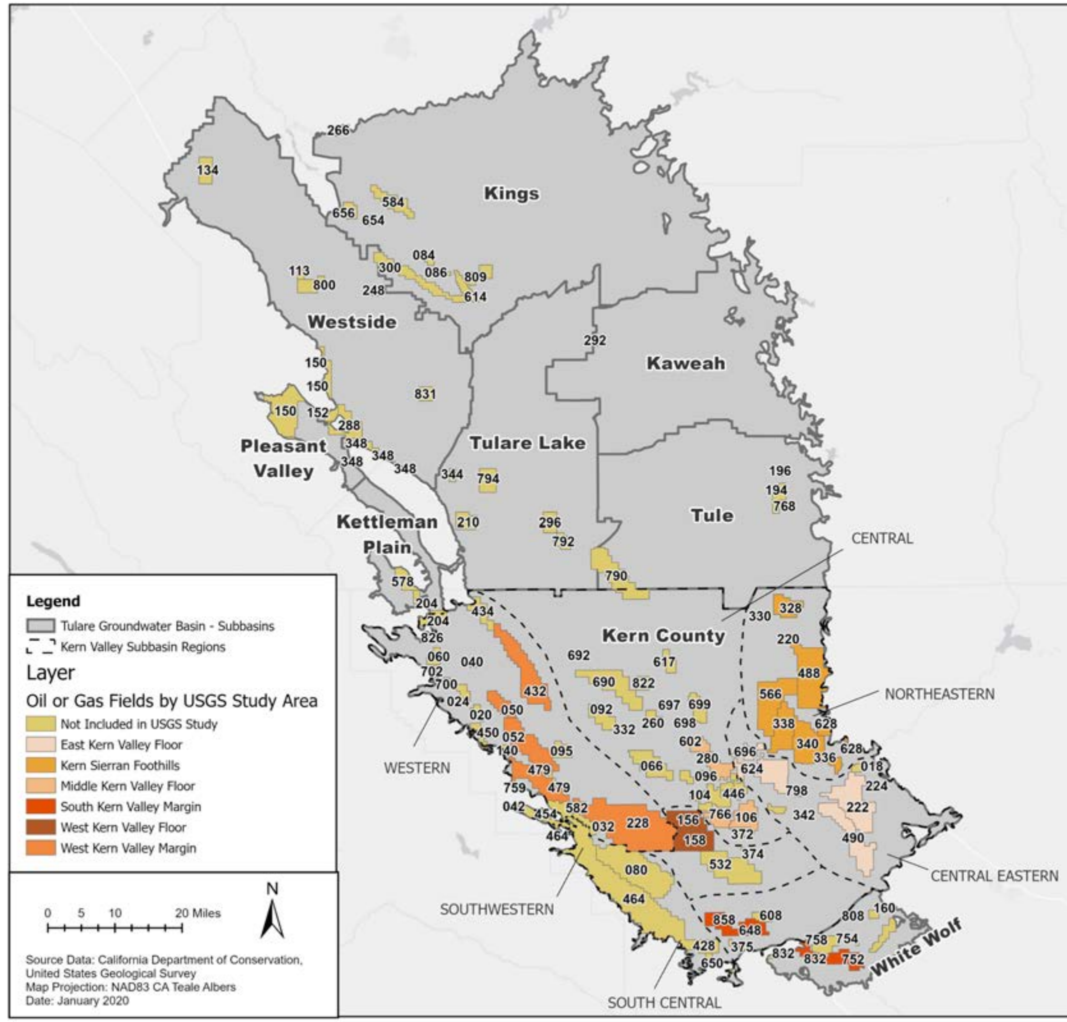


PSE

# Groundwater Subbasins in the Tulare Basin

The California Department of Water Resources created groundwater subbasins using geologic and hydrologic barriers or more commonly institutional boundaries for the purpose of managing water resources.

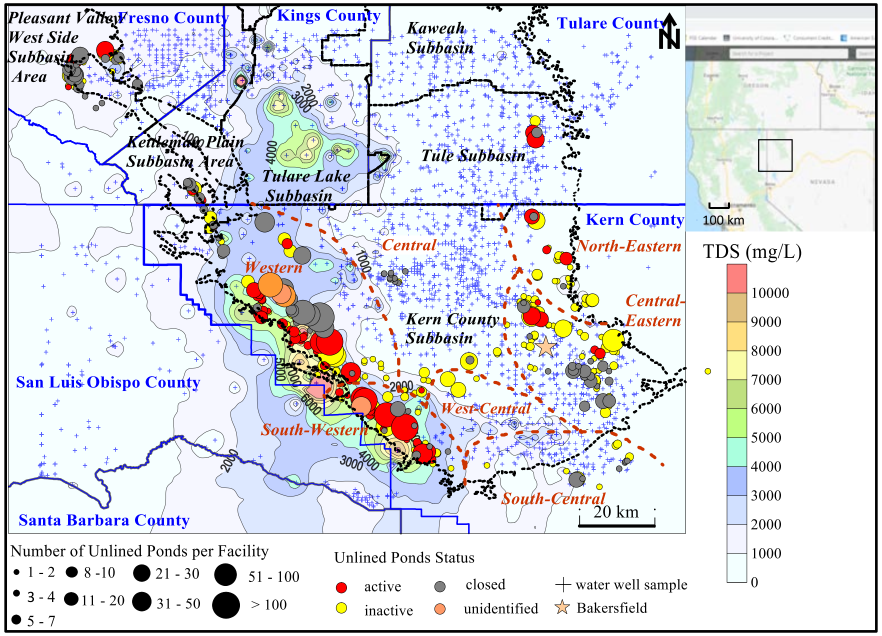
Portions of the Kern County Subbasin were subdivided in this investigation based on USGS groundwater resource investigations because of large number of ponds.

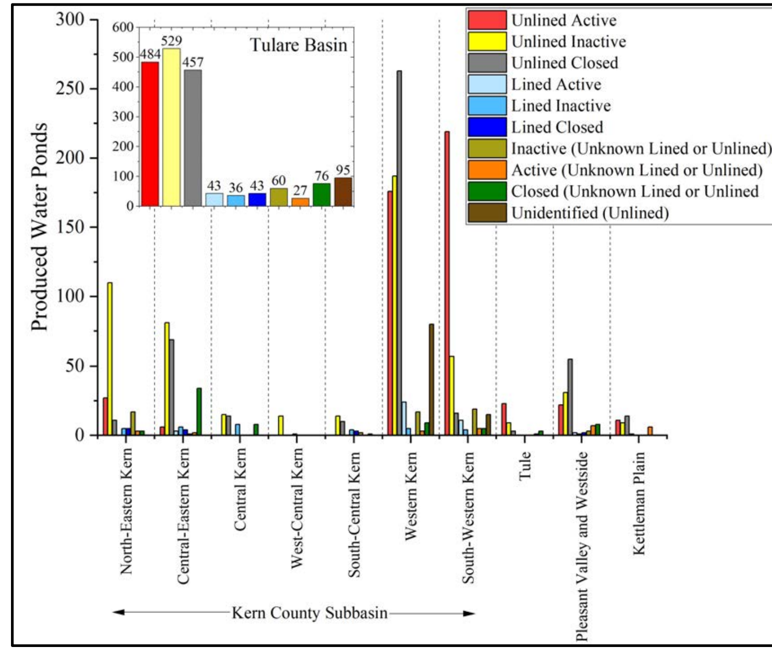


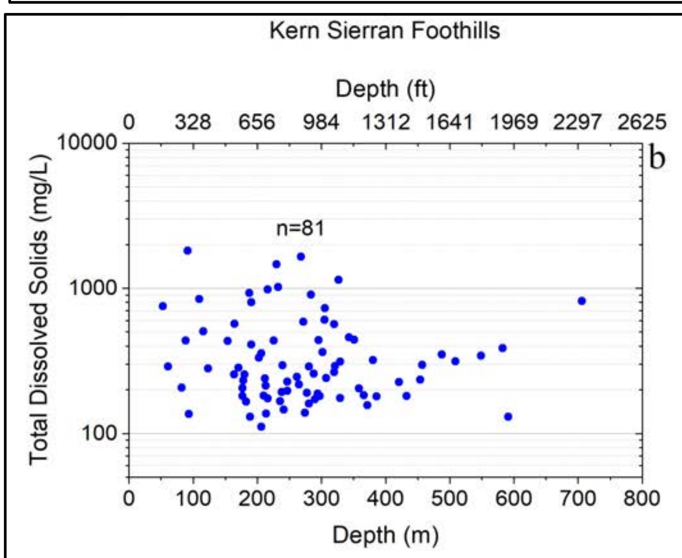

Outline of groundwater subbasins in the Tulare Groundwater Basin (solid lines) and areas within the Kern County Subbasin (dashed lines) and oil and gas fields in six USGS groundwater study areas (Metzger and Landon, 2018). Numbers in polygons refer to field codes of oil and gas fields. Figure from DiGiulio et al. (2021) (ES&T).

PSE

# North-Eastern Kern County Subbasin




Figures from DiGiulio et al. (2021) (ES&T).

181 ponds of which 148 are unlined of which 27 are still active.

At some fields in this area, produced water is blended with groundwater and surface water for irrigation.

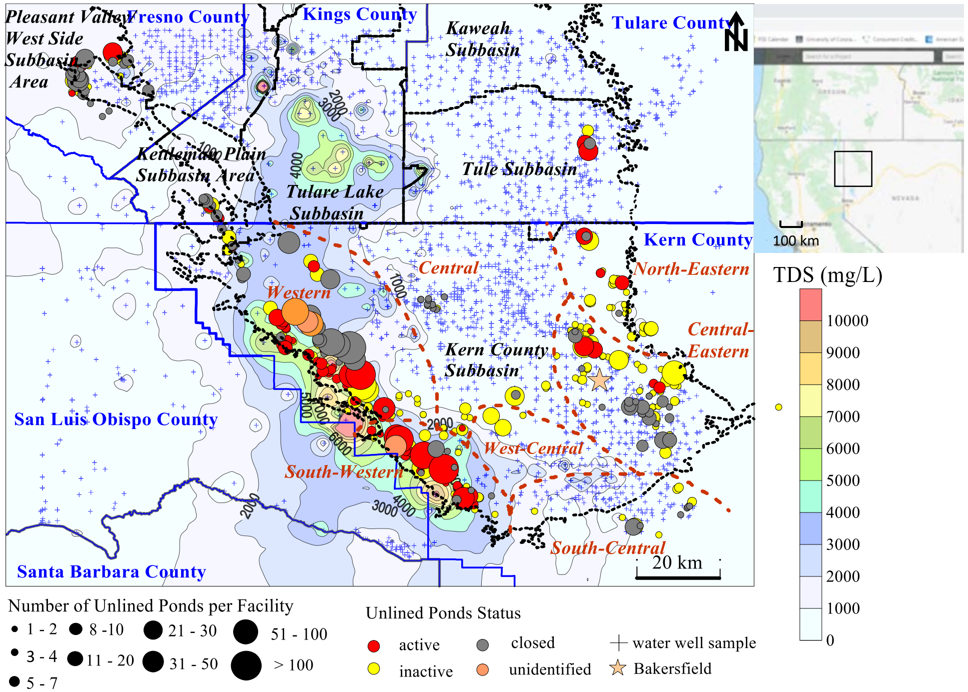
In the north-eastern Kern County Subbasin, TDS levels in groundwater are generally <1000 mg/L to a depth ~ 700 m.

No groundwater monitoring of unlined ponds used for disposal.

**Effluent Limit (EC: 1000 µS/cm, Cl: 200 mg/L, B: 1.0 mg/L)**

| Effluent | Medians | Max |
|---|---|---|
| EC (µS/cm) | 550-894 | 1800 |
| TDS (mg/L) | 360-573 | 6400 |
| Chloride (mg/L) | 56-128 | 1400 |
| Boron (mg/L) | 0.24-1.4 | 7.9 |
| Benzene (µg/L) | | <10 |
| Toluene (µg/L) | | 200 |
| Ethylbenzene (µg/L) | | 13 |
| Xylenes (µg/L) | | 95 |

# South-Central, Central, West-Central Kern County Subbasin



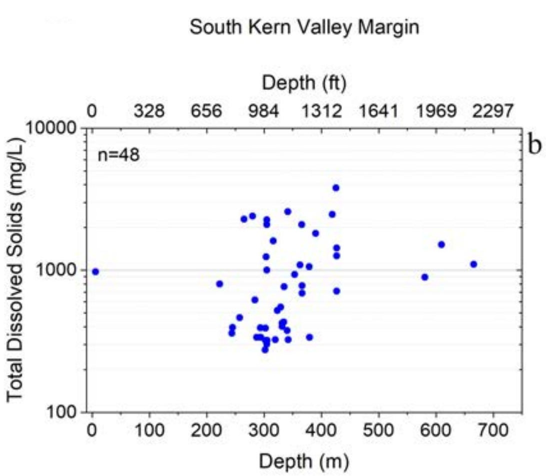

In the south-central area, TDS <3000 mg/L to ~700 m. In central area, TDS <3000 mg/L to ~250 m,. In west-central area, TDS <3000 mg/L to ~350m.

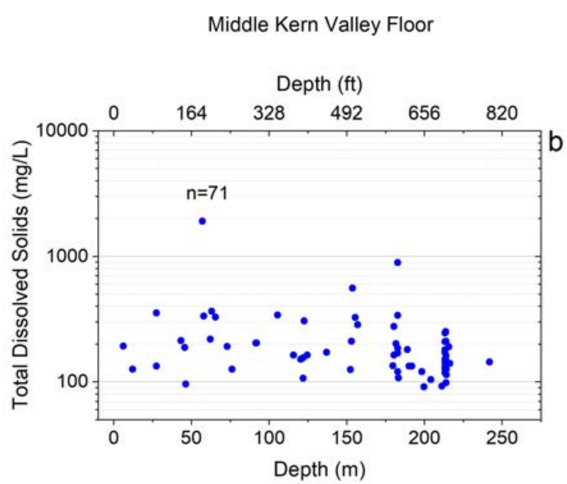
Primary concern 67 inactive and closed unlined ponds.

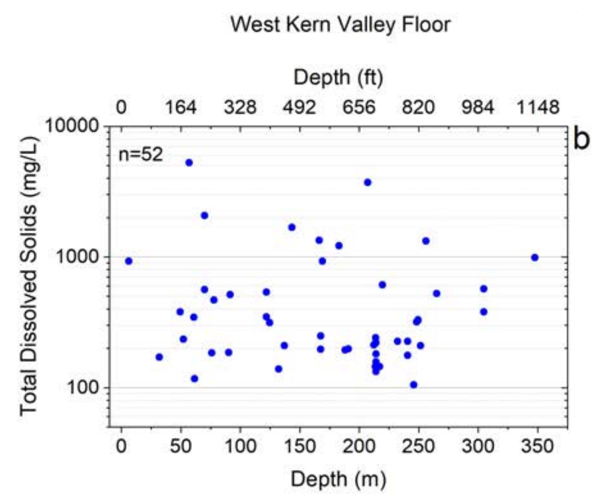
No historic effluent data but produced water is saline in this area indicating saline water likely disposed in unlined ponds.

No groundwater monitoring.

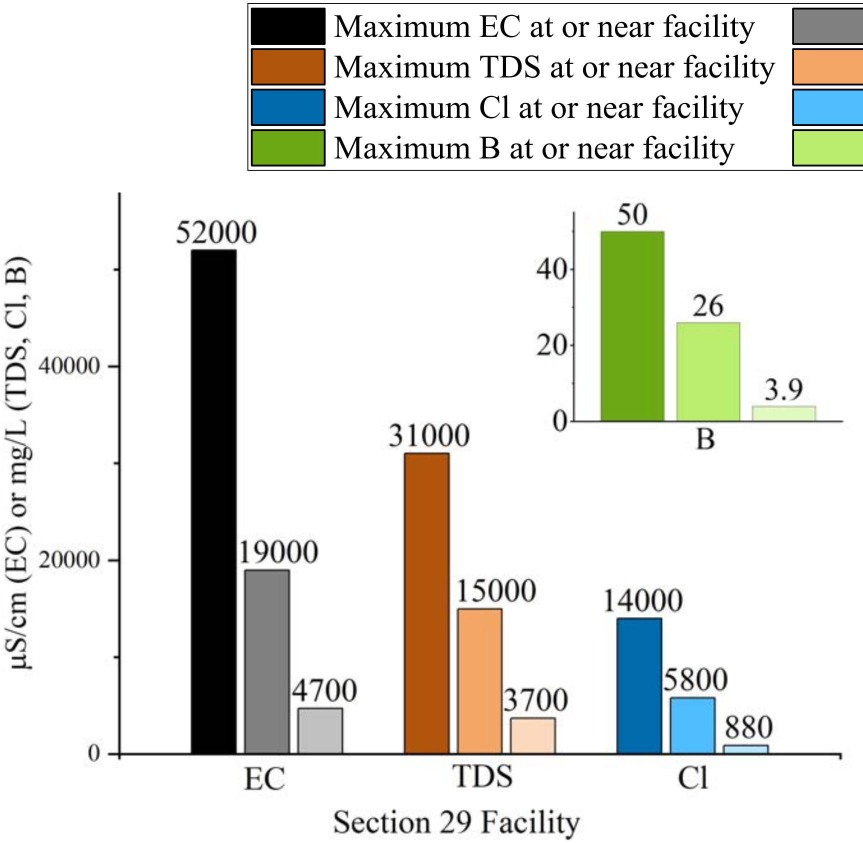
Figures from DiGiulio et al. (2021) (ES&T).

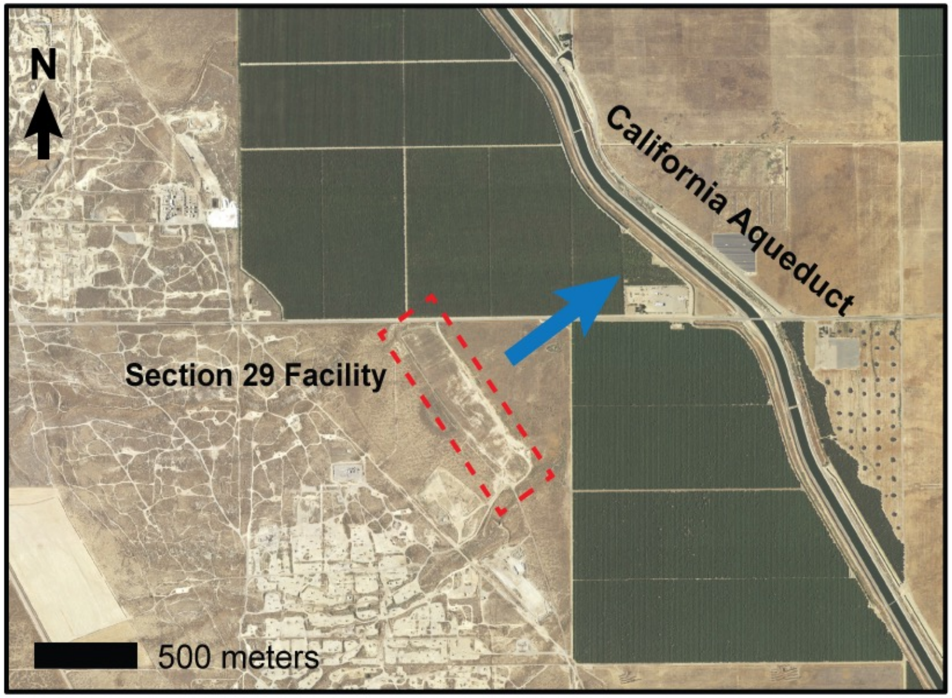


# Section 29 Facility



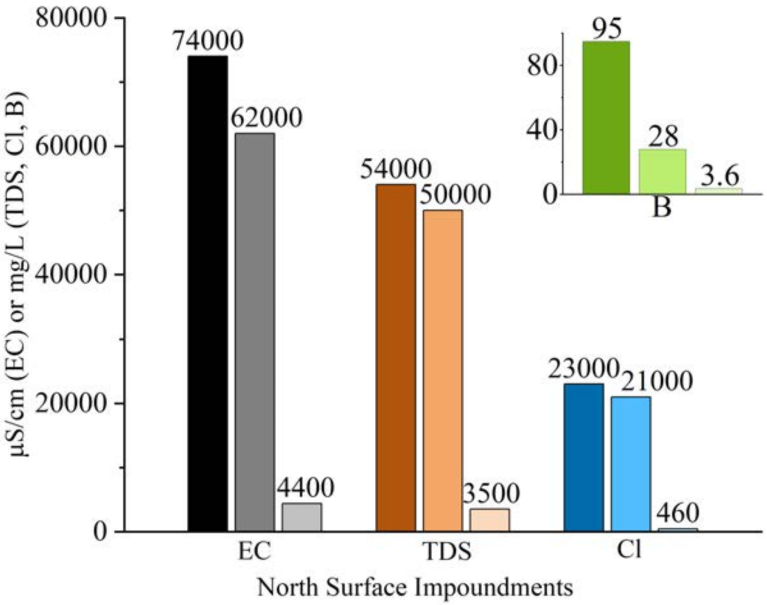

Figures from DiGiulio et al. (2021) (ES&T).

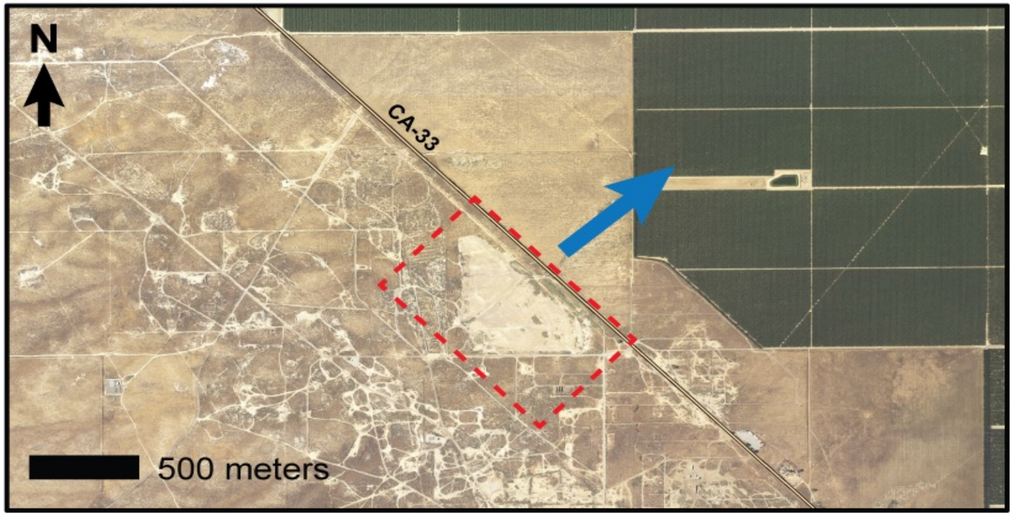
The closed **Section 29 Facility** located east of the Lost Hills Field in operation between the early 1960s and 2008 consisted of 8 unlined ponds and received ~4 MMbbls/yr.

Elevated levels of EC, TDS, Cl, and B in alluvium ~1.7 km northeast of the facility. BTEX components, and other hydrocarbons (e.g., naphthalene, methyl naphthalenes, trimethylbenzenes) detected in groundwater within ~0.5 km of the facility boundary. Unimpacted monitoring wells ~1.8 km from facility.

PSE

# North Surface Impoundments Facility



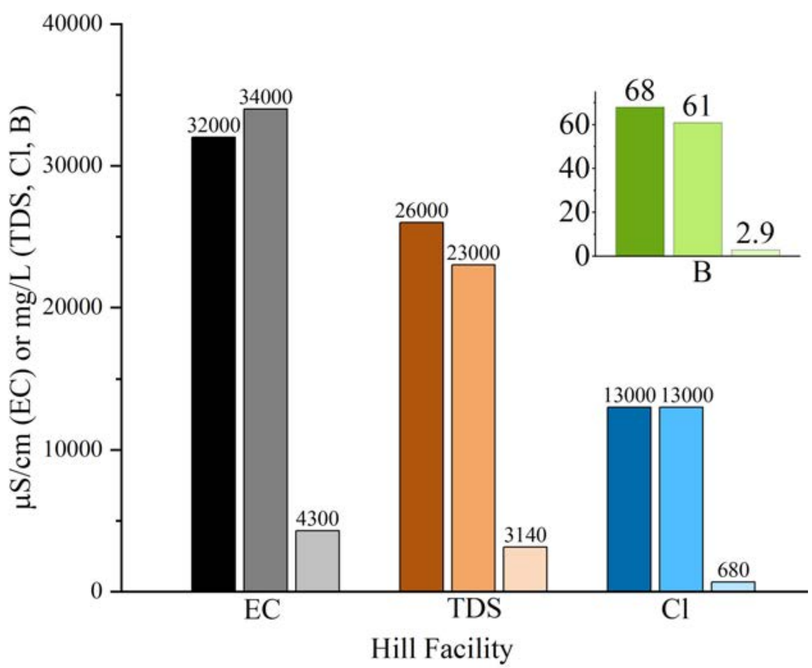

Figures from DiGiulio et al. (2021) (ES&T)

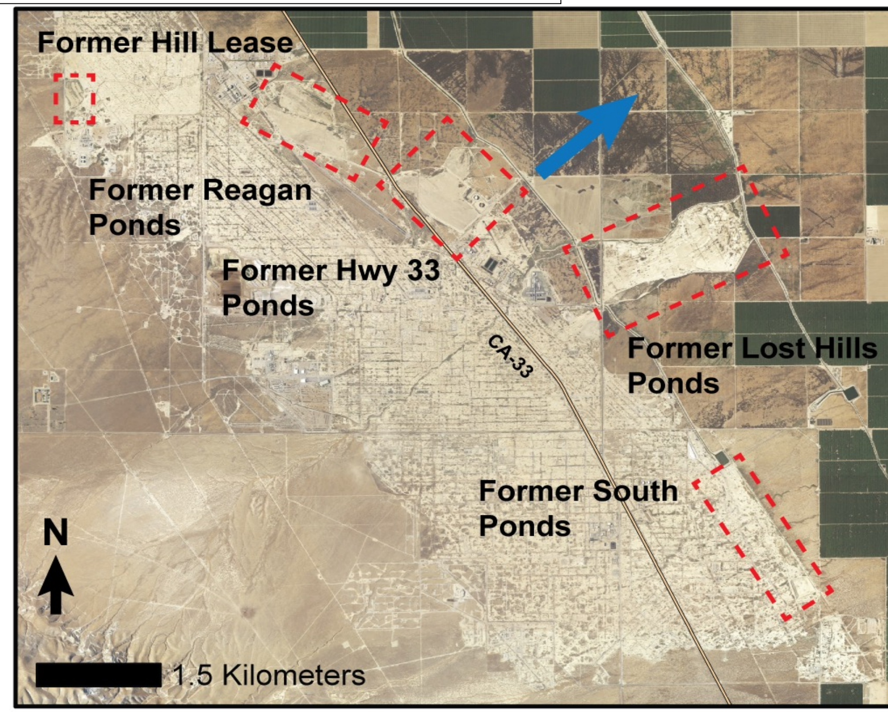
The closed **North Surface Impoundments Facility** located east of the Belridge North Field in operation between the early 1960s and 2011 consisted of 16 unlined ponds and received ? MMbbls/yr.

Elevated levels of EC, TDS, Cl, and B in alluvium ~1.5 km northeast of facility. Benzene detected at 360 µg/L at monitoring well ~1.3 km northeast of facility. Unimpacted well ~3 km northeast of the facility.

# Hill Facility

Figures from DiGiulio et al. (2021) (ES&T)




The closed **Hill Facility** located in the Belridge South Field in operation between the early 1960s and 2006 consisted of 4 unlined ponds and received 1.6 MMbbls/yr.

Elevated levels of EC, TDS, Cl, and B in alluvium ~0.5 km northeast of facility. Benzene detected at 45 µg/L at monitoring well ~0.5 km northeast of facility. Unimpacted well ~1.4 km northeast of the facility. Figure from DiGiulio et al. (2021) (ES&T).

Active remediation deemed too expensive ($24,000,000) so monitored natural attenuation chosen ($674,000) chosen to address contamination.

# McKittrick 6 & 6A, 6B,7 New, and 7 Old

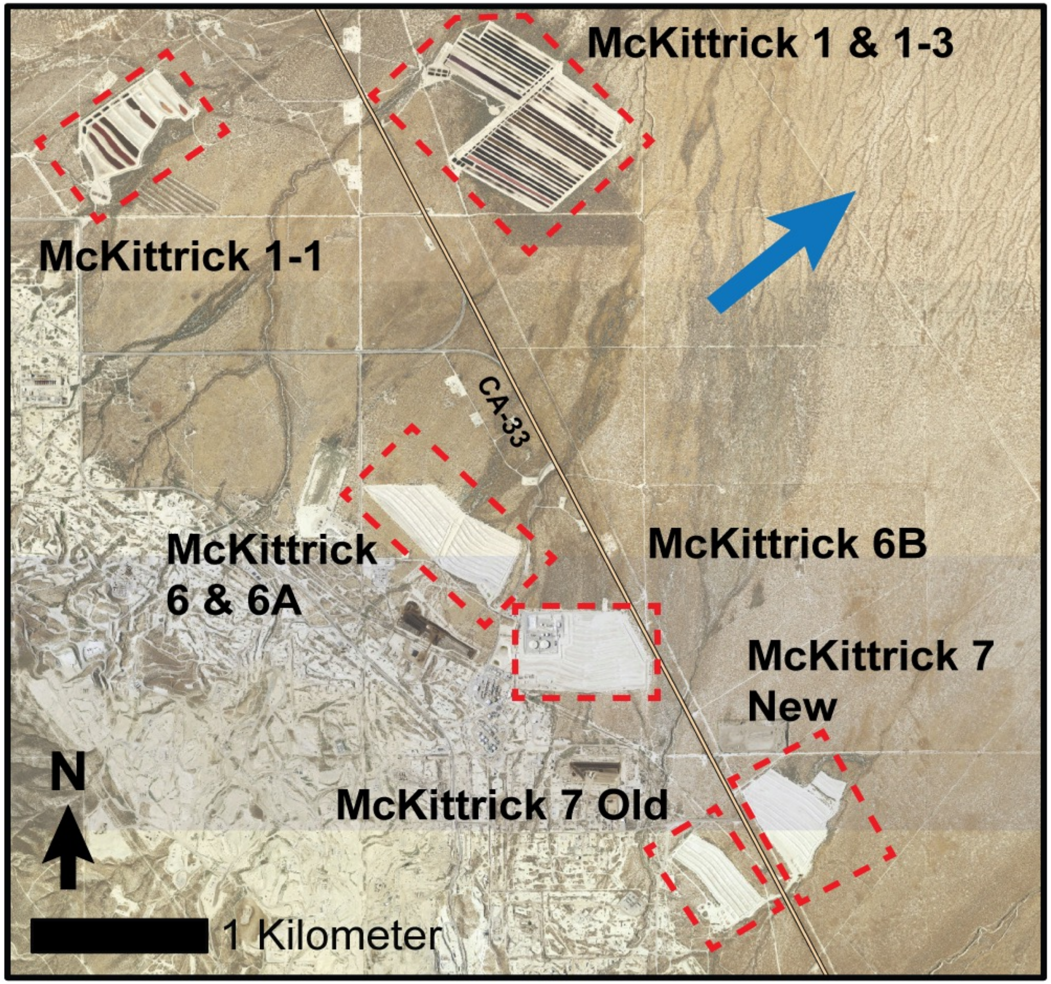
A large complex of inactive facilities is located directly south of the McKittrick 1-1 and 1 & 1-3 Facilities.

The **McKittrick 6, 6A, and 6B Facility** have been in operation since the late 1960s, consist of 56 unlined ponds and received 36.5 MMbbls in 2001.

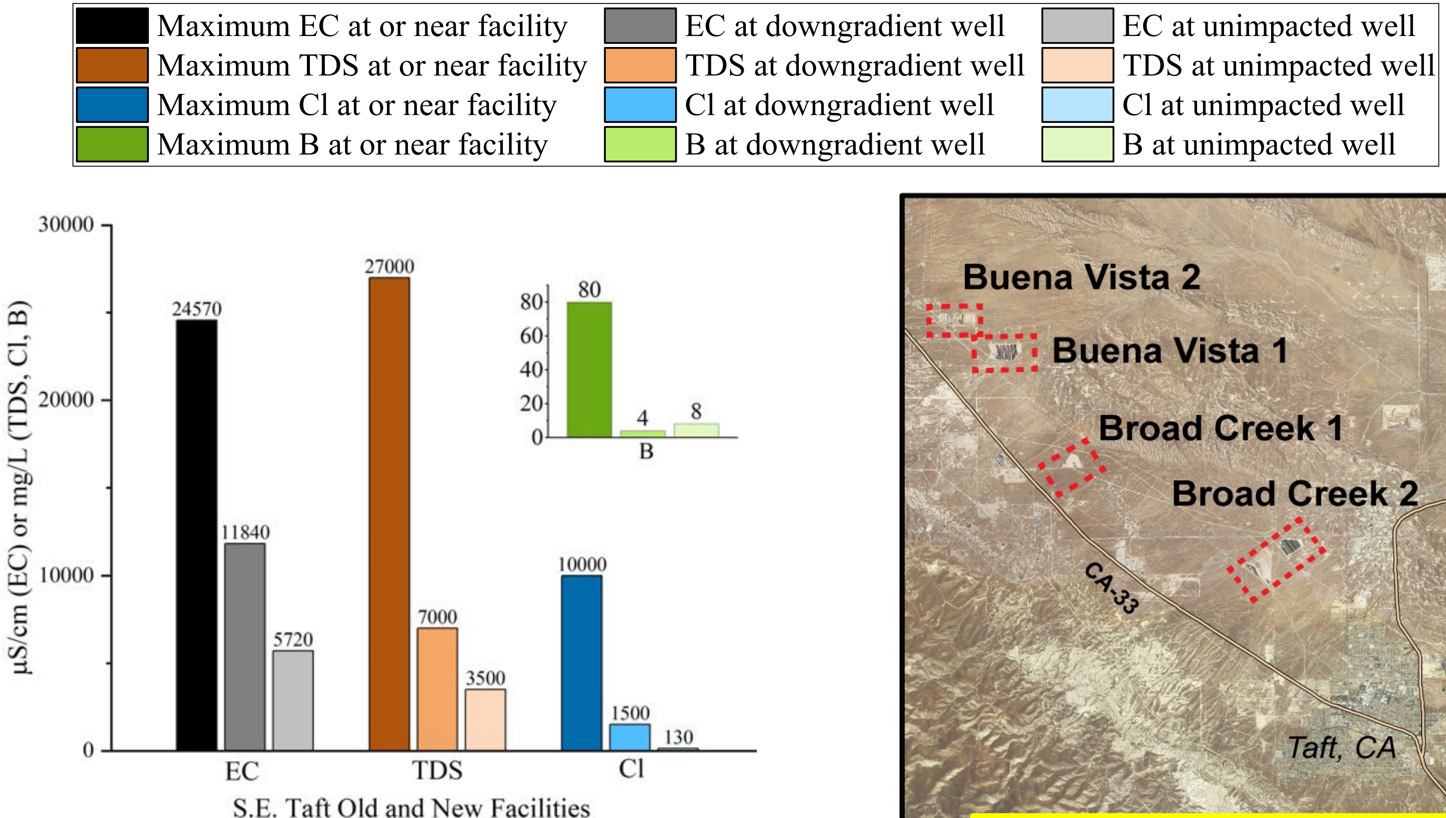
The **McKittrick 7 Old and 7 New Facility** consists of 38 unlined ponds and received 5.5 MMbbls in 2001.

The facility operator intends to close these facilities. Available documentation to date indicates no plans to install monitoring wells at these facilities.

Based on available discharge records, cumulatively, at least 4.75 billion barrels of produced water have been disposed in unlined ponds in the McKittrick ponds over a 60-year period.



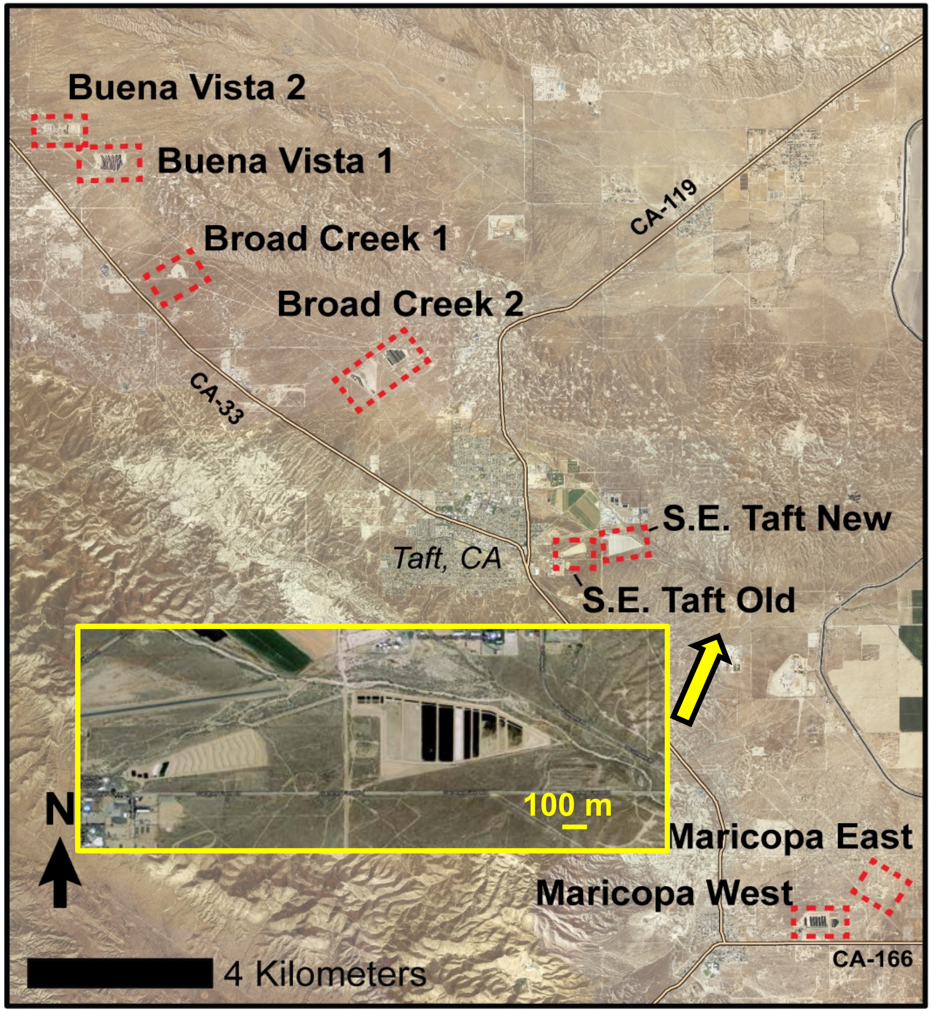
# S.E. Taft Old and New Facilities



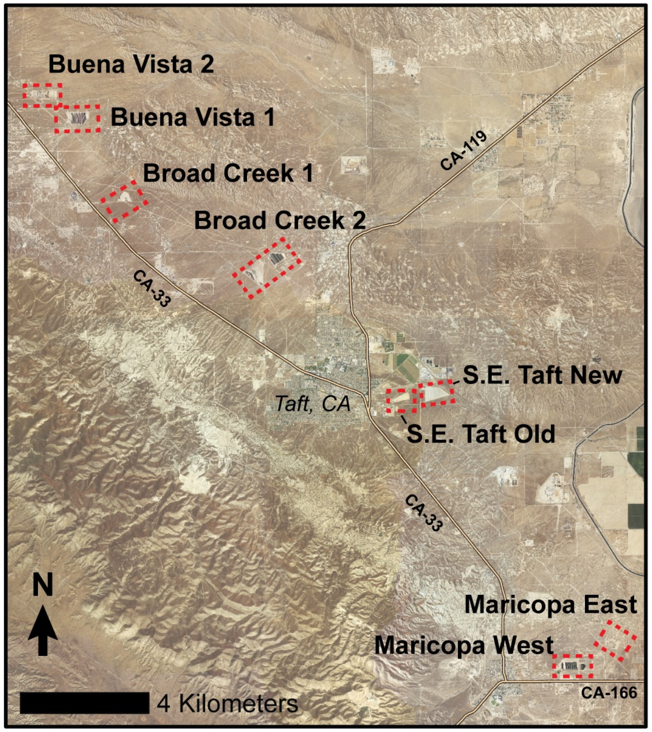

The **S.E. Taft Old Facility** has been in operation since 1959, consists of 30 unlined ponds, and discharges ~6.2 MMbbls/yr.

The **S.E. Taft New Facility** has been in operation since 1961, consists of 29 unlined ponds, and discharges ~4.4 MMbbls/yr.

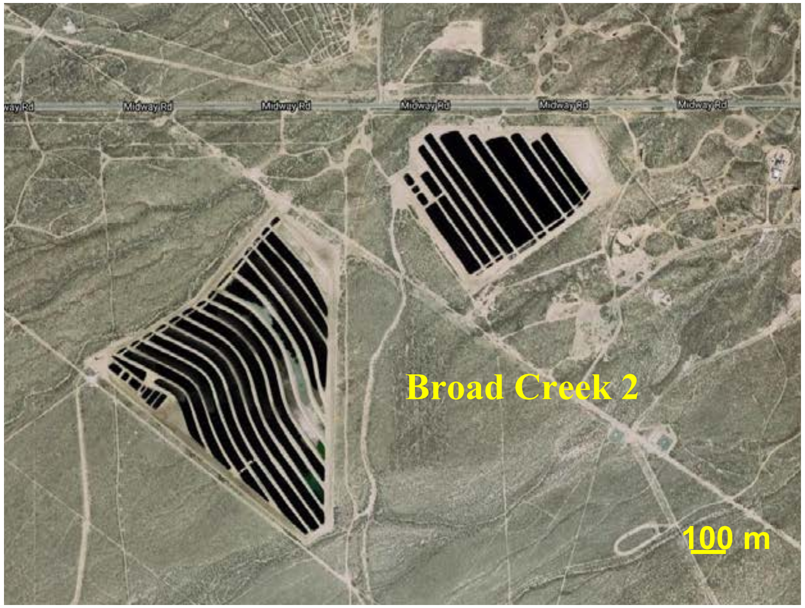
Elevated levels of EC, TDS, Cl, and B in perched alluvium ~1.2 km southeast of the S.E. Taft New Facility. Unimpacted well ~2.7 km southeast of the facility.



# Buena Vista and Broad Creek Facilities

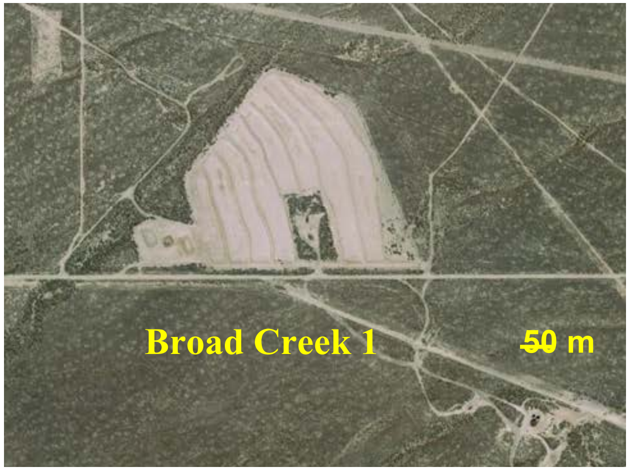

**Buena Vista 1 Facility**: 39 unlined ponds, **Buena Vista 2:** 27 unlined ponds, combined discharge ~19 MMbbls in operation since late 1950s.



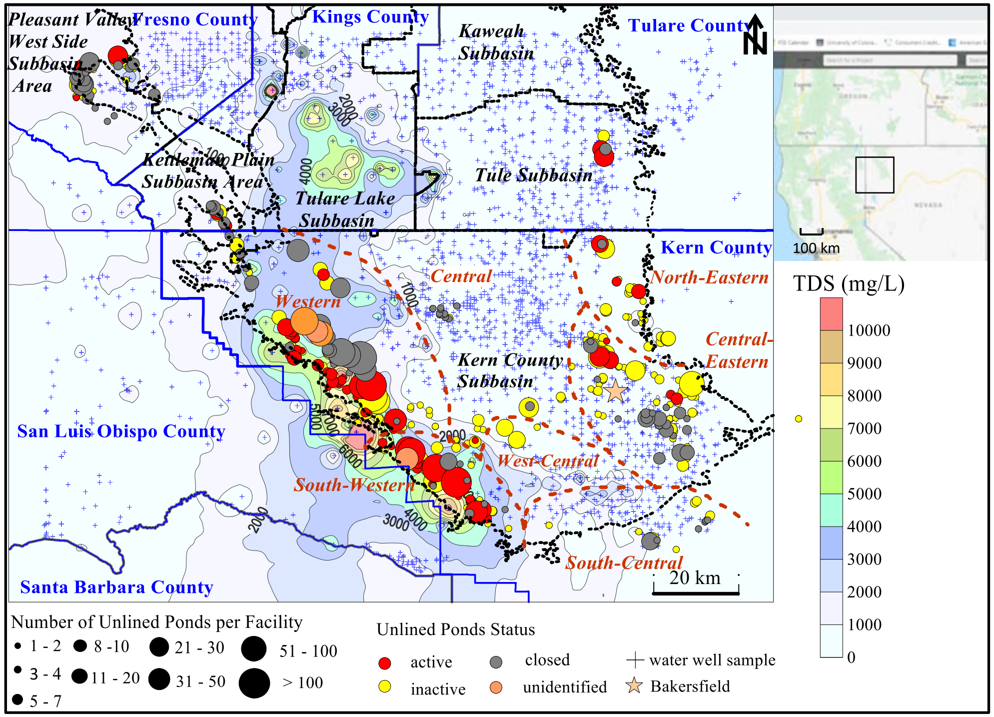

**Broad Creek 2 Facility**: 37 unlined ponds, combined discharge ~12 MMbbls/yr

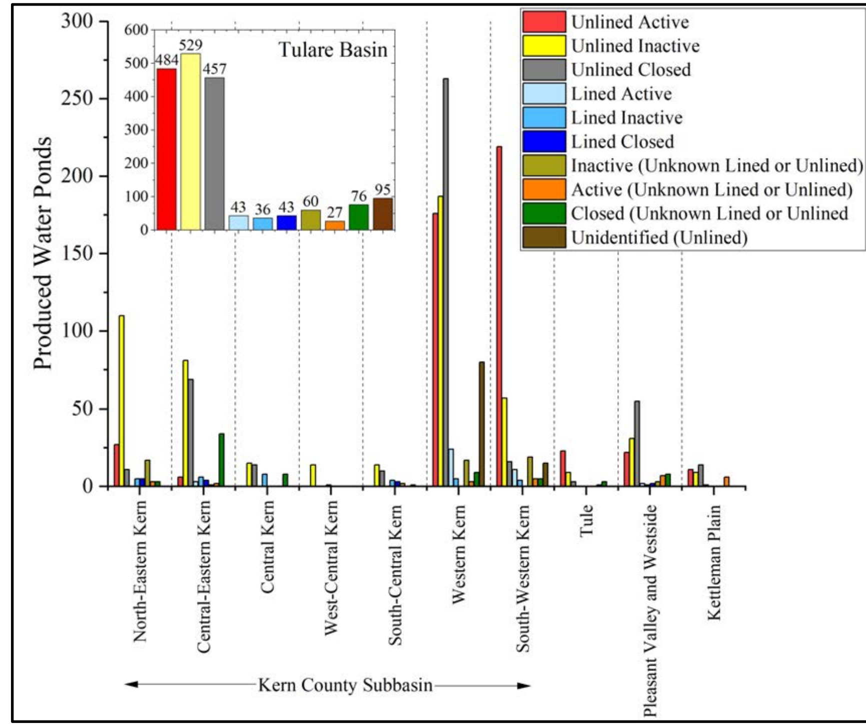
**Broad Creek 1 Facility**: 11 unlined ponds

No groundwater monitoring at any of these facilities.



# Tule Subbasin




Unlined ponds associated with the Deer Creek Field.

39 ponds of which 35 are unlined of which 23 are still active.

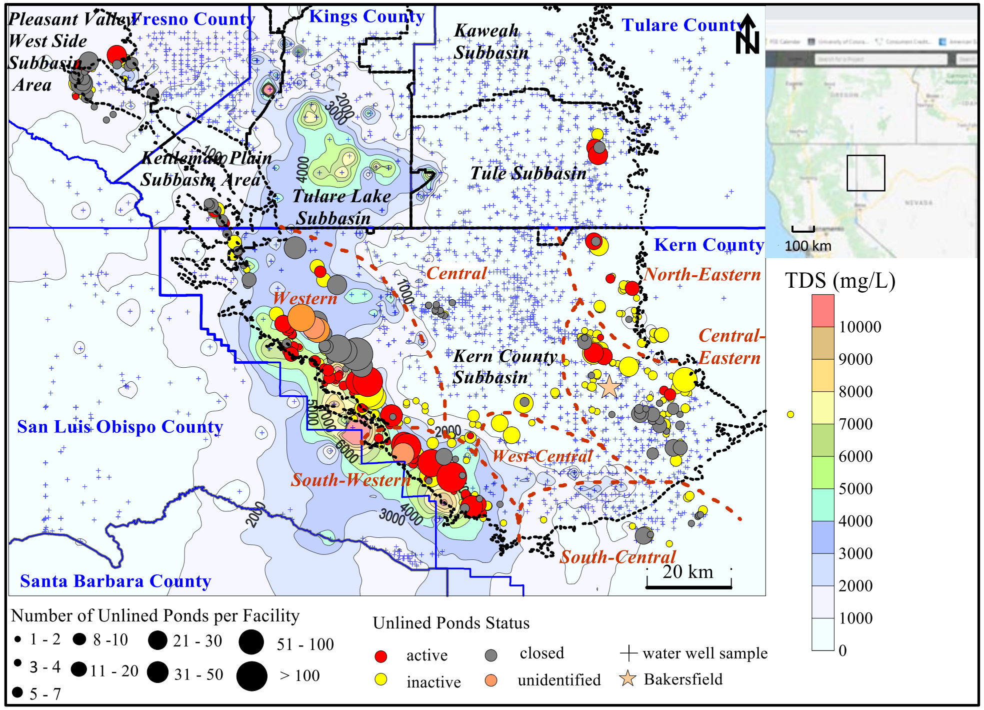
No area-wide clay layers to restrict vertical movement.

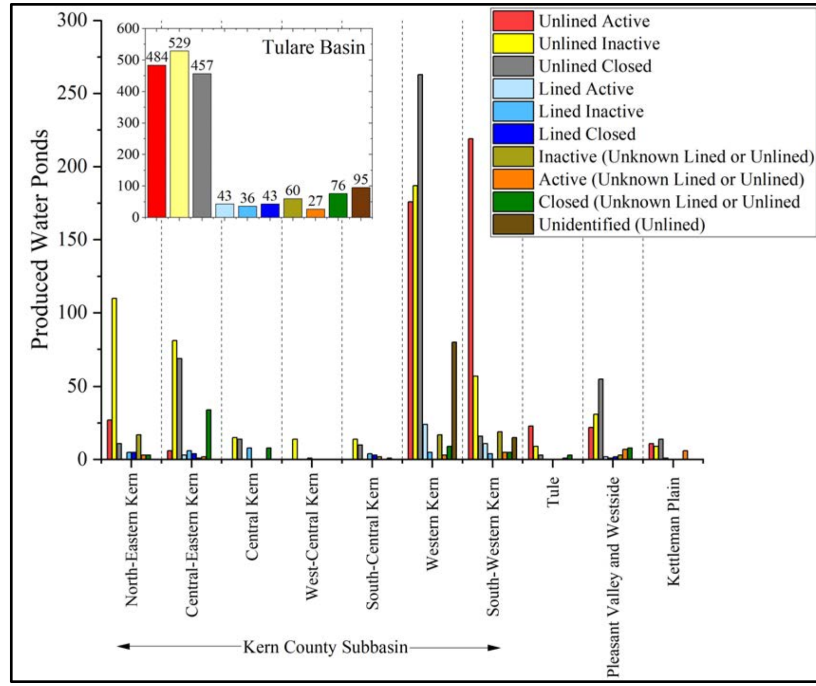
No groundwater monitoring.

**Effluent Limits (EC: 1000 µS/cm, Cl: 200 mg/L, B: 1.0 mg/L)**

| Effluent | Medians | Maximum |
|---|---|---|
| EC (µS/cm) | 500-680 | 940 |
| TDS (mg/L) | 310-405 | 3298 |
| Chloride (mg/L) | 30-130 | 1954 |
| Boron (mg/L) | 0.66-0.89 | 3.2 |
| Benzene (µg/L) | | 1.3 |
| Toluene (µg/L) | | 120 |
| Ethylbenzene (µg/L) | | 57 |
| Xylenes (µg/L) | | 240 |

# Pleasant Valley and West Side Subbasin Area




Most unlined ponds in this area are situated on anticlinal structures and are associated with the Coalinga Field.

131 ponds of which 108 are unlined of which 22 are still active.

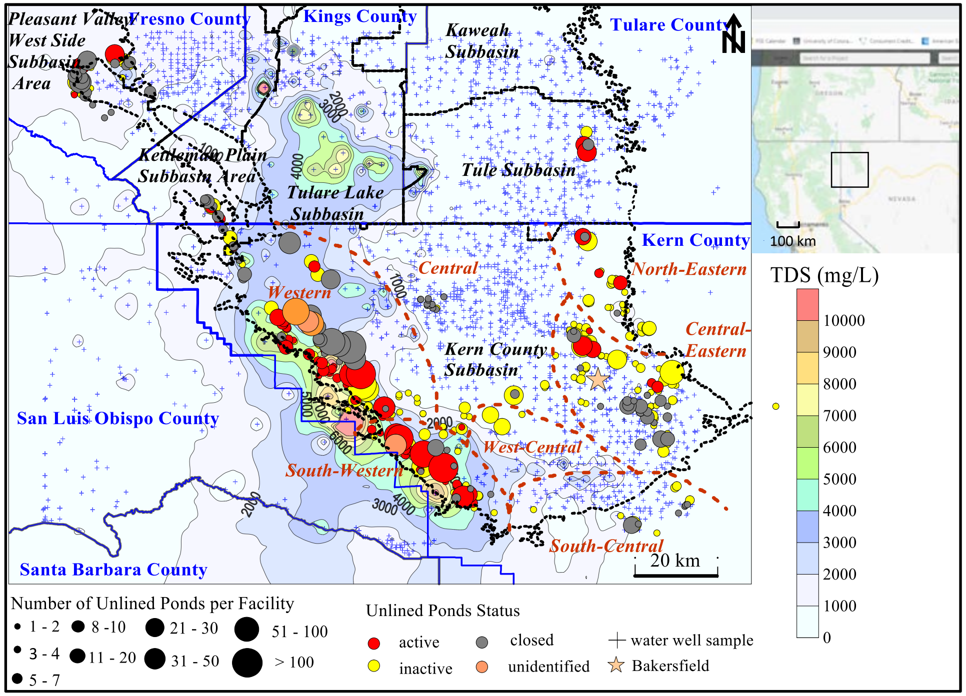
Facility operators have argued that groundwater is of "poor" quality and that disposal poses little risk to "potable" groundwater.

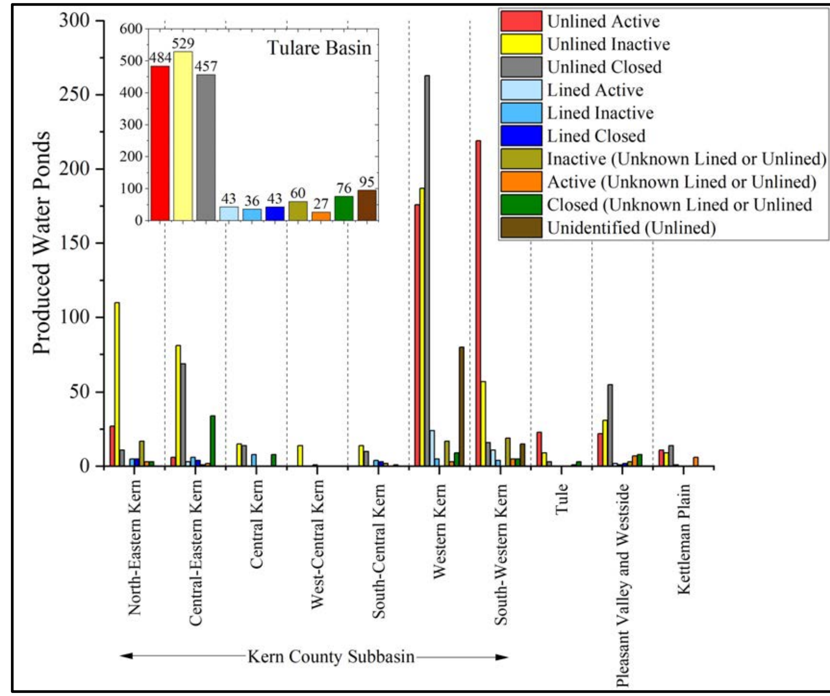
No groundwater monitoring.

**Effluent Limits (EC: 1000 µS/cm, Cl: 200 mg/L, B: 1.0 mg/L)**

| | Medians | Maximums |
|---|---|---|
| EC (µS/cm) | 5650-29000 | 71000 |
| TDS (mg/L) | 3800-12000 | 38000 |
| Chloride (mg/L) | 254-6100 | 22000 |
| Boron (mg/L) | 6.4-62 | 170 |
| Benzene (µg/L) | | 210 |
| Toluene (µg/L) | | 180 |
| Ethylbenzene (µg/L) | | 79 |
| Xylenes (µg/L) | | 180 |

# Kettleman Plain Subbasin Area




The primary field is the Pyramid Hills Field contains 41 ponds of which 34 are unlined of which 11 are still active.

Facility operators state that first encountered groundwater is oil bearing.

There is no groundwater monitoring to confirm the presence or absence of groundwater having beneficial use.

**Effluent Limits (EC: 1000 µS/cm, Cl: 200 mg/L, B: 1.0 mg/L)**

| | Medians | Maximums |
|---|---|---|
| EC (µS/cm) | 12500-18500 | 31000 |
| TDS (mg/L) | 7850-12500 | 23000 |
| Chloride (mg/L) | 2100-4400 | 6700 |
| Boron (mg/L) | 12-20 | 29 |
| Benzene (µg/L) | | 88 |
| Toluene (µg/L) | | 62 |
| Ethylbenzene (µg/L) | | 30 |
| Xylenes (µg/L) | | 191 |