Expert Recommendations for Groundwater Monitoring Criteria under SB4

State Water Resources Control Board
(July 7, 2015; CalEPA, Sacramento, CA)

Brad Esser (LLNL)

Lawrence Livermore National Laboratory

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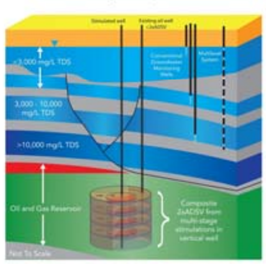
LLNL has submitted a final report with recommendations

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], Janice M. Gillespie[4], Robert B. Jackson[5], Preston D. Jordan[2], 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



Prepared in cooperation with the
California State Water Resources Control Board
LLNL-TR-669645

June 2015

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LLNL used both internal and external expertise to develop recommendations

Lawrence Livermore National Laboratory	CSU Bakersfield
Dr. Bradley K. Esser, Lead Dr. Joseph Morris Dr. Susan Carroll Vic Madrid, PG, CHG	Dr. Jan Gillespie **Stanford University** Dr. Rob Jackson
Lawrence Berkeley National Laboratory Dr. William T. Stringfellow Preston D. Jordan, PG, CHG, CEG Dr. Harry Beller Dr. Charu Varadharajan	**Duke University** Dr. Avner Vengosh **University of Guelph** Dr. Beth Parker Dr. John Cherry

Short bios are on the SWRCB SB4 website

LLNL is the scientific expert chosen by the State

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LLNL also engaged with stakeholder groups to develop recommendations

- **Public Stakeholder Meetings**
  - — Bakersfield (August 7, 2014)
  - — Los Angeles (August 25, 2014)
  - — Sacramento (December 11, 2014)
- **Private Stakeholder Meetings**
  - — LLNL and experts, SWRCB, WSPA, USGS (November 10, 2014; Sacramento)
  - — LLNL and experts, WSPA (February 10, 2015; Livermore)
  - — LLNL and experts, NRDC, CWA, EWG (February 25th, 2015; Berkeley)
  - — LLNL and experts, USGS, SWRCB (March 12, 2015; Livermore)
- **Informational Meeting**
  - — Sacramento (April 8, 2015)
- **Conferences**
  - — GRAC Symposium on Oil, Gas and Groundwater in California (February 19, 2015)
  - — Pacific Section AAPG: Mixing Oil and Water (May 3, 2015)
- **Reports release**
  - — Draft report for public review (June 19, 2015)
  - — Final report (June 30, 2015)

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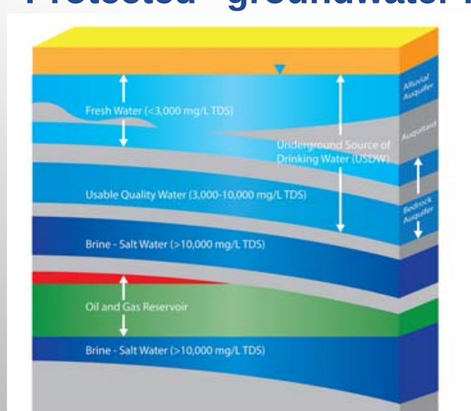
What groundwater should be monitored?

- **The relevant standards are for groundwater (not drinking water)**
  - —Beneficial use as a municipal or domestic water supply (<3,000 mg/L TDS)
  - —Underground Source of Drinking Water (<10,000 mg/L TDS)
- **We recommend monitoring groundwater up to 10,000 ppm TDS**
  - — Contains fewer than 10,000 mg/l total dissolved solids
  - — Sufficient quantity of ground water for beneficial use
  - — No exemption for hydrocarbon-bearing groundwater
- **Rationale**
  - —California is in the midst of an historic drought
    - — Desalination of brackish groundwater is technically feasible
  - —Consistent with protected groundwater in Underground Injection Control

A key consideration is that groundwater with beneficial use should be monitored for impact

“Protected” groundwater needs to mapped



The distribution of “usable” groundwater (TDS = 3,000 to 10,000 ppm) is poorly known

- **Recommendations**
  - — **Groundwater monitoring plans should include data relevant to determining aquifer salinity**
  - —**The State should systematically determine the spatial and vertical distribution of usable (3,000 - 10,000 mg/L) groundwater in all basins containing oil & gas fields**

More than one plan required

Scale	Responsibility	What
Well by well, Neighbor	Well Operator (Permit)	An individual or small set of oil & gas wells
		A nearby water well
Regional	Water Board	Groundwater basin
		Oil & gas field

For "well by well", the DOGGR final rule requires approval of a groundwater monitoring plan by the Water Board

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Area-specific monitoring goals

- **We do not recommend that early detection of leakage from an individual stimulation be a primary goal**

  —Requires development of a site conceptual model

  — This is currently difficult because of scale and data availability

  —Real-time pressure testing at the time of well stimulation will detect ***major*** loss of fluids out of the target zone

Defining monitoring goals determines monitoring network design

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Area-specific monitoring goals

- **We do recommend monitoring for impact of well stimulation on groundwater at an area-wide scale**

  — **Groundwater monitoring is still necessary**
  - — Well stimulation has the potential to impact groundwater
  - — Real-time pressure testing will not detect **minor** loss of fluids

  —**Baseline characterization is critical to detecting impact**
  - — Spatial and temporal variability
  - — Legacy impacts

Detecting impact will require characterizing baseline water quality

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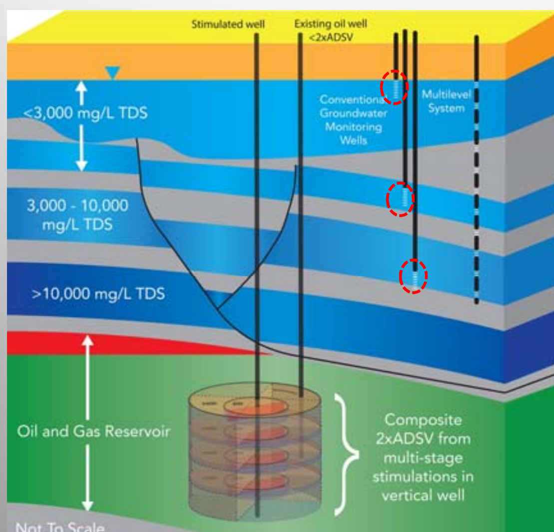
In our recommendations, a typical stimulation would require monitoring three aquifers



Aquifers to be monitored

Highest quality (lowest TDS) groundwater

Base of freshwater (0-3,000 mg/L TDS)

Base of protected water (3,000-10,000 mg/L TDS)

Multiple aquifers will require
- Multiple monitoring wells or,
- A multi-level monitoring system (see report appendix)
- We do not recommended nested wells in a single borehole

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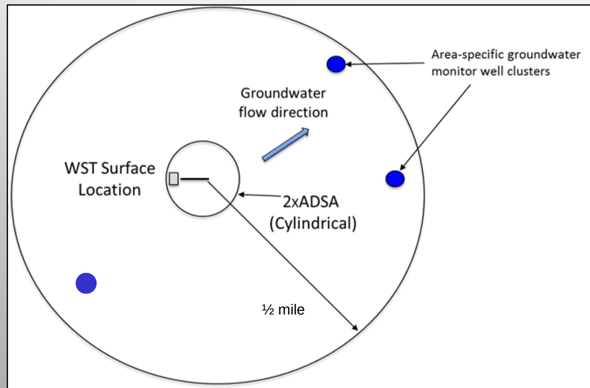
We recommend groundwater monitoring wells be located within one half mile of the stimulated well



We recommend one up-gradient and two down-gradient wells in each monitored aquifer.

Closely-spaced stimulation wells can "share" groundwater monitoring wells.

We also recommend the use of "guard" wells between stimulated wells and water supply wells.

Three groundwater monitoring wells will allow assessment of spatial variability in water quality

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Risk-based groundwater monitoring

- **Monitoring should be tiered by risk**
  - — Stimulated wells with higher probability of impacting groundwater should be monitored more intensively
    - — Very high risk operations should not be permitted
  - — Higher quality groundwater should be monitored more intensively
- **What is more intense monitoring?**
  - —Monitoring closer to the stimulated well
  - — Monitoring more aquifers overlying the stimulation zone
  - —Monitoring more locations in each aquifer

We recommend higher levels of monitoring for higher levels of risk

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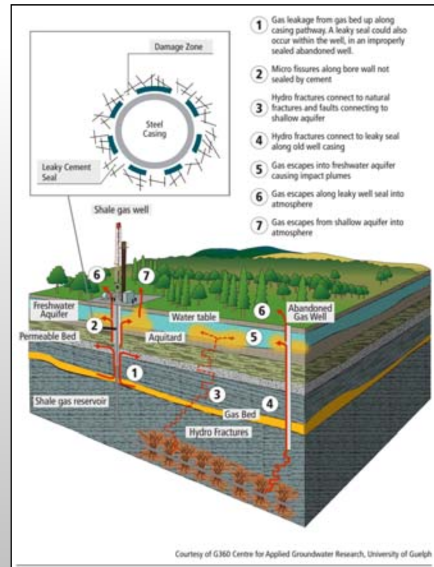
What determines risk?

- **Potential transport pathways** in close proximity to the stimulation
- **Well stimulation density** close to the stimulation
- **Vertical separation** between the stimulated zone and protected groundwater



Contaminant transport pathways were considered in prioritizing risk factors

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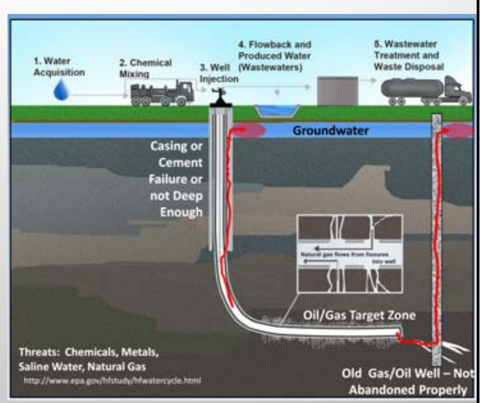
Risk: Transport pathways in close proximity

Contamination Source/Pathway	Shallow	Intermediate, Deep
Oil & gas wells	**X**	**X**
Inactive and abandoned wells	**X**	**X**
Natural fractures & faults	X	X
Hydrofracturing	X	X



Inadequately constructed or abandoned wells in close proximity to a stimulated well are of greatest concern

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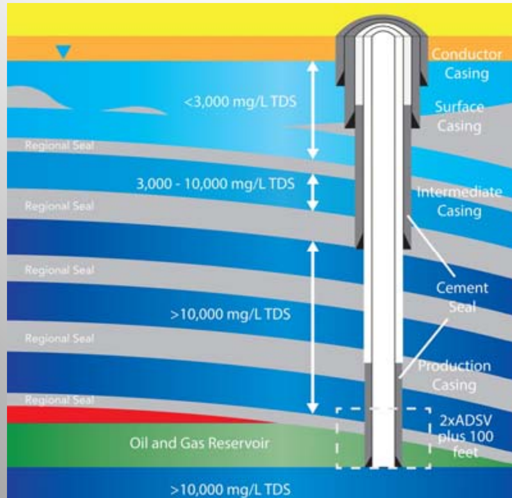
What is "inadequate" construction for offset wells?



We recommend use of the Groundwater Protection Standard (DOC Draft EIR)

The outer annular space be filled with cement from the surface to a confining unit below groundwater with 10,000 mg/L TDS

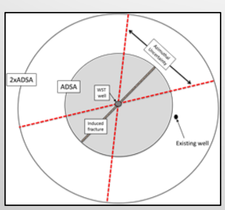
The annular space of the production casing be filled with cement from the top of the stimulation zone up to at least 100 feet into a regional seal or 500 feet, whichever is longer

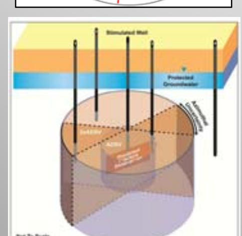
Wells that meet this standard are "potential" pathways. Wells that do not meet this standard are "likely" pathways.

What is "in close proximity" for offset wells?

- **"Close proximity" is defined by the dimensions of the stimulated zone**

We recommend that …



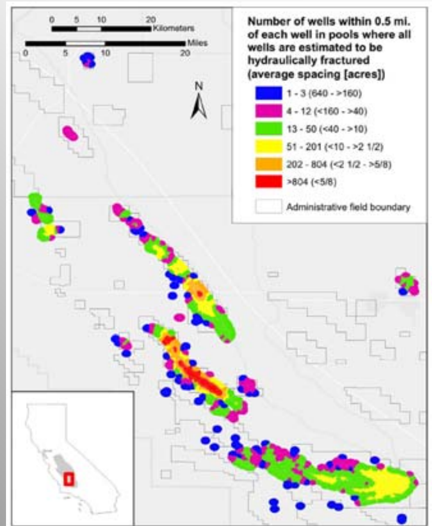


Estimation of the **Axial Dimensional Stimulation Area (ADSA)** using a geomechanical model be validated by field data, and that azimuthal angle uncertainty be submitted along with maximum length, height and thickness; **or**

When field data are not available, a conservative cylindrical estimate of stimulated volume be used that assumes azimuth is not known.

Close proximity is within 2xADSA for wells, and within 5xADSA for geologic features

Risk: Well Density



The number of stimulated wells within ½ mile of a stimulated well in California varies by orders of magnitude (from less than 4 to more than 800 wells)

Protected groundwaters overlying oil fields with high stimulation well densities should be monitored more intensively. We recommend monitoring of a third aquifer at the base of freshwater for these fields.

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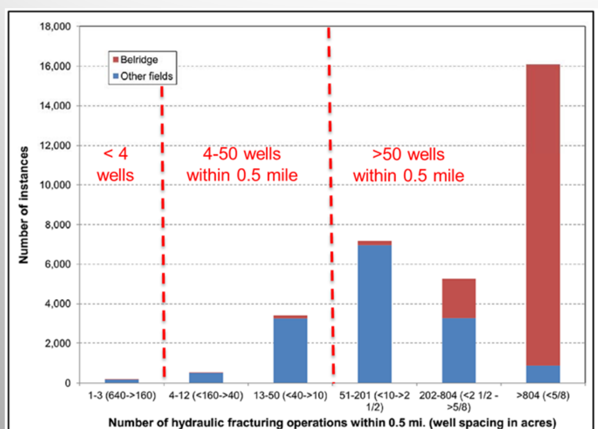
Most well stimulations are in high-density fields



Protected groundwaters overlying fields with high stimulation well densities should be monitored more intensively. We recommend monitoring of a third aquifer at the base of freshwater for these fields

Most stimulated wells will have >50 previously stimulated wells within ½ mile. Very few stimulated wells will have <4 previously stimulated wells with ½ mile.

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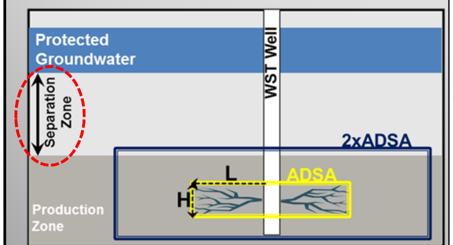
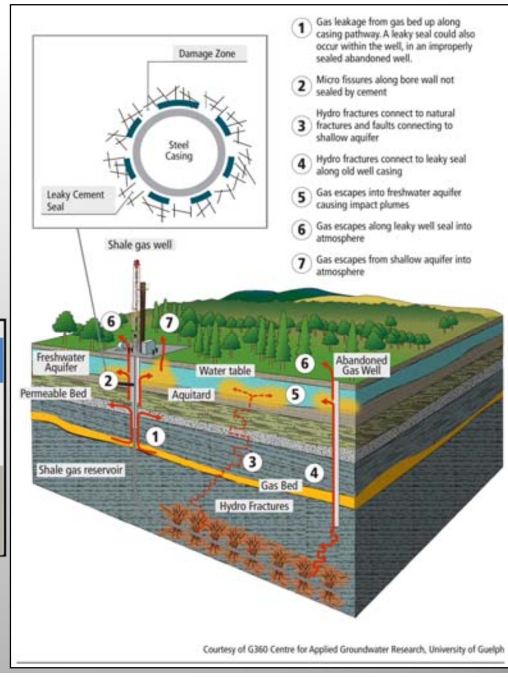
Risk: Vertical Separation

- Propagation of induced fractures into the protected groundwater.





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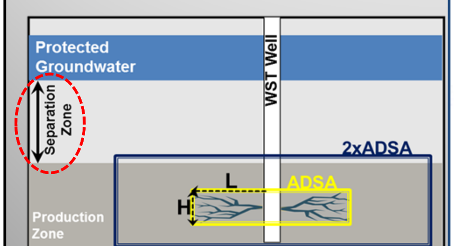
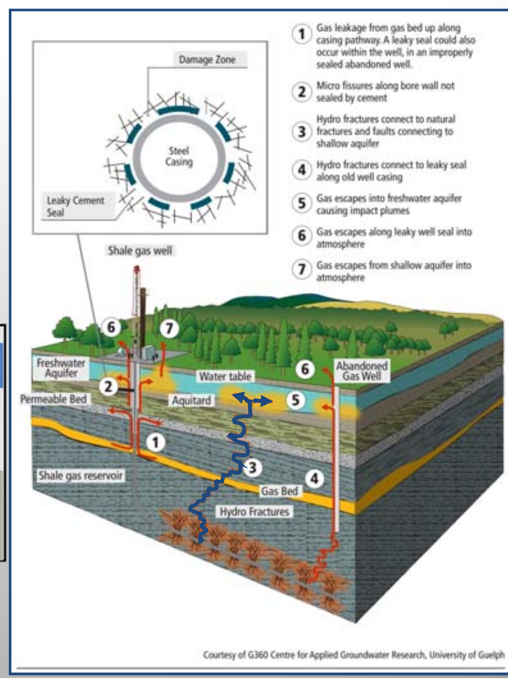
Risk: Vertical Separation

- Transport of injected fluids through transmissive geologic features.





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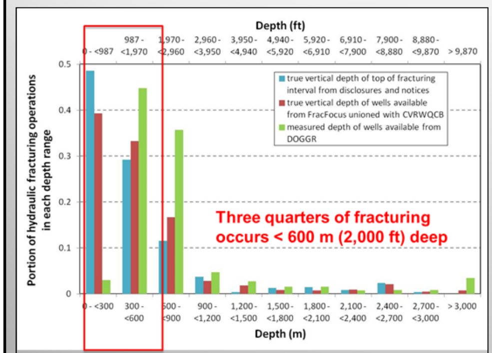
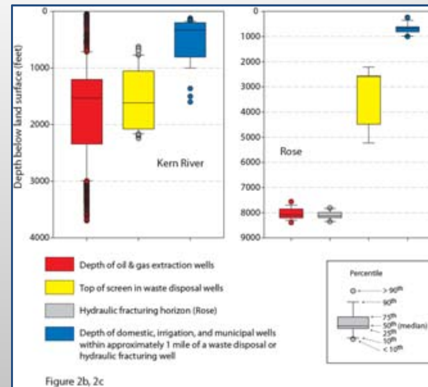
Vertical separation is potentially an issue in California

Stimulated wells in California tend to be shallow



Vertical separation varies by field



Taylor K. A., Fram M. S., Landon M. K., Kulongoski J. T. and Faunt C. C. (2014) ***Oil, Gas, and Groundwater in California - a discussion of issues relevant to monitoring the effects of well stimulation at regional scales.***, California Water Science Center, U.S. Geological Survey.

We recommend a minimum vertical separation of 2xADSV +100 feet

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Risk-based groundwater monitoring

Vertical Separation	Pathways in close proximity	Previous WST within 0.5 mile	Aquifers monitored and # locations per aquifer: High-Quality Freshwater	Aquifers monitored and # locations per aquifer: Base of Freshwater	Aquifers monitored and # locations per aquifer: Deep protected	Type of well
>2xADSV+ 100 ft	None known	<4	3	0	0	Regional or Area
		4 to 50	3	0	3	
		>50	3	3	3	
	Potential	<4	3	0	3	Area
		4 to 50	3	0	3	
		>50	≥3	≥3	≥3	
	Likely	Additional review required. WST may not be allowed or additional monitoring of at-risk aquifers may be required				
≤2xADSV+ 100 ft	WST not allowed					

Monitoring requirement will vary from site to site

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Risk-based groundwater monitoring

Vertical Separation	Pathways in close proximity	Previous WST within 0.5 mile	Aquifers monitored and # locations per aquifer			Type of well
			High-Quality Freshwater	Base of Freshwater	Deep protected	
>2xADSV+ 100 ft	None known	<4	3	0	0	Regional or Area
		4 to 50	3	0	3	
		>50	3	3	3	
	Potential	<4	3	0	3	Area
		4 to 50	3	0	3	
		>50	≥3	≥3	≥3	
	Likely	Additional review required. WST may not be allowed or additional monitoring of at-risk aquifers may be required				
≤2xADSV+ 100 ft	WST not allowed					

A minimum vertical separation should be required for a plan to be approved.

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Risk-based groundwater monitoring

Vertical Separation	Pathways in close proximity	Previous WST within 0.5 mile	Aquifers monitored and # locations per aquifer			Type of well
			High-Quality Freshwater	Base of Freshwater	Deep protected	
>2xADSV+ 100 ft	None known	<4	3	0	0	Regional or Area
		4 to 50	3	0	3	
		>50	3	3	3	
	Potential	<4	3	0	3	Area
		4 to 50	3	0	3	
		>50	≥3	≥3	≥3	
	Likely	Additional review required. WST may not be allowed or additional monitoring of at-risk aquifers may be required				
≤2xADSV+ 100 ft	WST not allowed					

All well stimulations should require monitoring of at least two aquifers:
A high quality, low-TDS aquifer and an aquifer at the base of protected water.

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Risk-based groundwater monitoring

Vertical Separation	Pathways in close proximity	Previous WST within 0.5 mile	Aquifers monitored and # locations per aquifer			Type of well
			High-Quality Freshwater	Base of Freshwater	Deep protected	
>2xADSV+ 100 ft	None known	<4	3	0	0	Regional or Area
		4 to 50	3	0	3	
		>50	3	3	3	
	Potential	<4	3	0	3	Area
		4 to 50	3	0	3	
		>50	≥3	≥3	≥3	
	Likely	Additional review required. WST may not be allowed or additional monitoring of at-risk aquifers may be required				
≤2xADSV+ 100 ft	WST not allowed					

Well stimulations in high stimulation density fields should require monitoring of three aquifers, including one at the base of freshwater.

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Risk-based groundwater monitoring

Vertical Separation	Pathways in close proximity	Previous WST within 0.5 mile	Aquifers monitored and # locations per aquifer			Type of well
			High-Quality Freshwater	Base of Freshwater	Deep protected	
>2xADSV+ 100 ft	None known	<4	3	0	0	Regional or Area
		4 to 50	3	0	3	
		>50	3	3	3	
	Potential	<4	3	0	3	Area
		4 to 50	3	0	3	
		>50	≥3	≥3	≥3	
	Likely	Additional review required. WST may not be allowed or additional monitoring of at-risk aquifers may be required				
≤2xADSV+ 100 ft	WST not allowed					

Well stimulations with improperly sealed or abandoned wells in close proximity would require additional review and remedial action or additional monitoring

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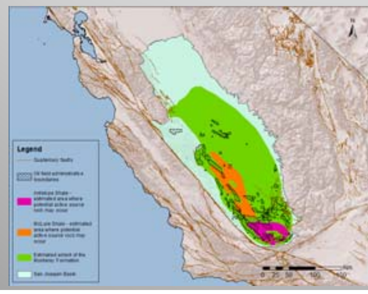
Two important points on monitoring design

- **Alternative groundwater monitoring plans should be allowed**
  - — To the extent that a credible Site Conceptual Model (SCM) can be developed, we recommend that operators be allowed and encouraged to propose alternative SCM-based groundwater monitoring plans.
- **If well stimulation in California changes, the monitoring criteria should also change**
  - —Example: Using high-volume, multi-stage, horizontal hydrofracture to access unconventional oil in deeper, low-permeability sources…



San Joaquin Basin source rock:
Monterey data from Magoon et al. (2009)

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What constituents should be analyzed?

- **Considerations in analyte choice**
  - — Regulated constituents
  - — Unregulated toxic or stimulation-specific constituents
  - — Potential for detectable impact from oil and gas operations
  - — Utility in distinguishing source of observed changes in water quality
- **Use a tiered approach**
  - — A first-tier set of analytes analyzed for every sample
    - — Commercial availability, ease of sampling, and cost
    - — Availability of standardized analytical protocols (EPA, ASTM, etc.)
  - — A second-tier set of analytes analyzed only if evidence for a statistically significant change in water quality is observed
    - — Toxic chemical additives associated with well stimulation
    - — Introduced tracers associated with well stimulation

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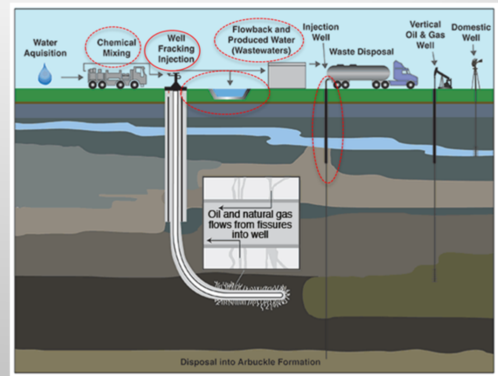
Working hypothesis: Impacts from produced water and gas leakage will be more prevalent and easier to detect than impact from injected water

Contamination Source/Pathway	Shallow	Intermediate, Deep
Wastewater: sumps	**X**	
Wastewater: injection	**X**	**X**
Oil & gas wells	**X**	**X**
Inactive and abandoned wells	**X**	**X**
Natural fractures & faults	X	X
Hydrofracturing	X	X



We have very little data on chemical additives in protected groundwaters…

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How is impact detected?

- **How is impact detected?**
  —Detecting statistically significant change in water quality consistent with impact
  —Confirming with additional analyses (e.g. of second-tier analytes)
- **Establishing a baseline is critical**
  —Determine variability to detect statistically significant change
  —Characterize legacy impacts
  —We recommend semi-annual monitoring for three years followed by a review of the data
- **We recommend a RCRA approach to detecting significant changes in water quality**
  —USEPA (2009) Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities: Unified Guidance, EPA 530/R-09-007.
  —Operator can also propose a method

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First-tier analytes: routine constituents

- **Field parameters** during sampling: **pH**, **T**, **EC**, DO, ORP, H_2S
- **Total dissolved solids**
- **Major and minor cations and anions**
- **Trace metals and metalloids** (including Fe, Mn, **Li**, **Sr**, **B**)
- **CCR Title 22 metals** (As, Ba, Cd, Cr, Pb, Hg, Se)
- **CCR Title 22 radionuclides** (Ra-226, Ra-228, and U);
- **PAHs** (polynuclear aromatic hydrocarbons)
- **BTEX** (benzene, toluene, ethylbenzene, and xylenes);
- **Total Petroleum Hydrocarbons** for gasoline and diesel ranges;
- **Methane**, ethane, propane;
- Dissolved organic carbon (DOC);
- Stable carbon isotopes in dissolved methane (if present);
- Stable isotopes of oxygen and hydrogen in water;

Analytes required in interim regulation in bold

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First-tier analytes: Rationale

Table 6.2 discusses methods, sample sizes, detection limits and rationale.

Analyte	Method (or equivalent)	Sample size (may vary)	Detection limit	Rationale
BTEX (benzene, toluene, ethylbenzene, xylenes), and Tentatively Identified Compounds[10]	EPA 8260 (purge-and-trap GC/MS)	40 mL (duplicate)	0.5 µg/L	Various BTEX compounds are used in hydraulic fracturing operations. These compounds are all designated as U.S. EPA Priority Pollutants. Baseline values will be needed to assess the impacts of well stimulation.
TPH (GRO-Gasoline Range Organics)[1]	EPA 8260 (purge-and-trap GC/MS)	See note 1	5 mg/L	Useful fingerprint of contamination by light (gasoline range) hydrocarbons, which may be helpful in distinguishing between contamination from ongoing O&G activities and well stimulation.
Methane, ethane, propane	RSK175	40 mL	1 µg/L	In other parts of the country, studies have shown that measurements of methane in groundwater can be an important indicator of leakage from well bores and other sources, such as fractures. Methane concentrations as high as 45 to 68.5 mg/L (ppm) have been observed in New York, West Virginia, and Pennsylvania groundwaters (Vidic et al., 2013). Coordinated studies examining methane concentrations and isotopic signatures of methane are a best practice in the development of a comprehensive groundwater monitoring program.
TPH (DRO - Diesel Range Organics)	EPA 8015 with solvent extraction	500 mL	1 mg/L	Useful fingerprint of contamination by diesel-range hydrocarbons, which may be helpful in distinguishing between contamination from ongoing O&G activities and well stimulation.

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First-tier analytes: special constituents

SB4 requires analysis of *"appropriate indicator compounds(s) for the well stimulation treatment fluid"*

- **Guar** (guar gum sugars)
  - The most common and abundant additive used in California
  - A simple analysis
- **Two chemical additives used in the well stimulation treatment**
  - Will allow documenting the presence or absence of well stimulation chemical additives in overlying protected groundwaters
  - Chosen by the operator on the basis of
    - Mass used in stimulation and
    - Persistence in the environment

Indicator Compounds

- **We recommend allowing the operator choose indicators**
  - Over 300 different chemicals or chemical mixtures were used for hydraulic fracturing between 2011 and 2014 in California,
  - A median of 23 individual additives were used per treatment

Table 5.3. Twenty reported hydraulic fracturing chemicals in California used in the largest masses, excluding base fluids (e.g. water and brines) and inert mineral proppants and carriers. [a] Derived from data collected and compiled by Stringfellow et al. (2015).

Chemical	CASRN	Treatments using this chemical	Total mass reported (kg)	Toxicity data available [b, c]
Guar gum	9000-30-0	1,376	1,788,995	RMDT
Phenol, polymer with formaldehyde	9003-35-4	203	724,439	R
Hydrochloric acid	7647-01-0	43	658,919	RDT
Potassium carbonate	584-08-7	255	643,257	RMDF
Hydrotreated light petroleum distillate	64742-47-8	1,035	532,222	RFT
Petroleum distillate blend	Proprietary	147	528,947	--
Distillates, petroleum, hydrotreated light paraffinic	64742-55-8	1,006	517,116	RDT
Methanol	67-56-1	379	421,551	RMDFT
Alkanes / alkenes	Proprietary	33	218,275	--

Second-tier analytes

- **Second tier analytes are analyzed if groundwater quality changes in a manner consistent with impact from WST**
- **Second-tier analytes were chosen on the basis of their toxicity and their uniqueness to well stimulation**
  - —Surfactants used during well stimulation
  - —Alcohols and glycols used during well stimulation
  - —Biocides used during well stimulation, including any of the following compounds and their known harmful or persistent degradation products:
    - — glutaraldehyde;
    - — DBNPA and its degradation products;
    - — isothiazolinones;
  - —Tracers used during well stimulation

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Regional monitoring components

- **Detect migration of oil & gas fluids out of “isolated” zones into protected groundwater**
  - —Does not distinguish between WST, EOR, and UIC
  - —Requires mapping of protected groundwater resources
- **Monitor impact of produced water ponds on shallow groundwater**
  - —Use GAMA Shallow Groundwater approach over more focused area
- **Investigate impact of well bore integrity on water quality**
  - —Will require study design
- **Develop regional-scale conceptual models for protected groundwaters and hydrocarbon producing zones**

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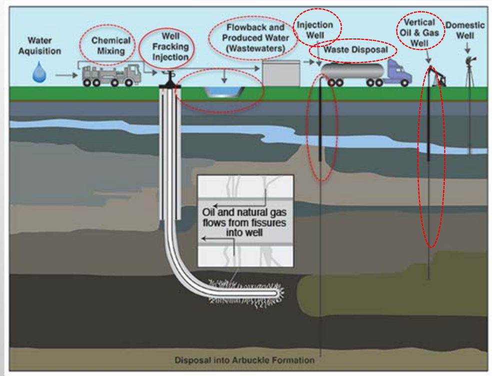
The regional program should monitor the impact of all oil & gas development on protected groundwater quality

- **The contaminant pathways of most concern to regional groundwater quality are not unique to well stimulation**
  - —Wastewater disposal through discharge to unlined sumps
  - —Wastewater disposal through underground injection into non-exempt aquifers
  - —Well integrity failure
- **A primary concern is salinity and natural constituents in formation fluids and produced fluids**



- **Many of the chemicals used in well stimulation are not unique to well stimulation**
  - —Biocides, surfactants

Prioritization of monitoring efforts

Initial monitoring efforts should

- Prioritize fields where well stimulation is currently practiced.
- Prioritize monitoring based on protected groundwater vulnerability.
- Prioritize monitoring fresh water protected groundwater aquifers
- Consider existing infrastructure, including existing monitoring programs

Time will be required to implement a long-term regional groundwater monitoring plan

Regional water quality monitoring

- **Water quality monitoring should be coordinated with other SB4 water quality monitoring efforts**
  - —Monitor all samples for analytes monitored in area program
  - —Monitor select samples for intrinsic tracers of source and transport
    - — *Isotopic composition of dissolved lithium, boron, sulfur, and strontium*
    - — *Concentration and isotopic composition of dissolved noble gases*
  - —Monitor select samples for toxic and indicator compounds
- **The regional monitoring program should have access to samples collected in other SB4 or UIC monitoring programs**
  - —Samples of injected fluid, produced water and groundwater
  - —Will allow analysis of non-routine analytes, e.g. intrinsic tracers such as noble gases and the isotopic composition of Li, B, S, and Sr
  - —Will require coordination with industry

SB4 monitoring programs should be coordinated

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The monitoring programs should be adaptive

- **California is leading the nation in regulation of well stimulation**
  - — Full disclosure of chemical additives
  - — Systematic groundwater monitoring of new well stimulation projects
  - — Regional groundwater monitoring of oil & gas fields
- **Monitoring a deep subsurface source is fundamentally different than monitoring a surface source**
  - —The hydrogeology and permeability of strata between currently used groundwater aquifers and oil and gas production zones is poorly known
  - —The distribution of brackish groundwater is poorly known,
  - —Available data needs to be compiled and digitized;
  - —Monitoring strategies need to vetted

Pilot studies and periodic program review will be important

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Pilot and Special Studies

Significant gaps exist in our understanding of the impact of oil and gas development on groundwater resources in California and in how to identify and monitor impacts.

- **The Regional Program should develop studies to**
  - —Improve monitoring of the impact of oil and gas operations on groundwater;
  - —Develop better understanding of aquifer vulnerability
- **The Regional Program should design and conduct these studies**
  - — In coordination with industry
  - — Under the guidance of a Technical Advisory Committee
  - —In collaboration with USGS, the national laboratories and universities

Pilot and special studies are necessary to develop a credible and protective monitoring program

Pilot and Special Studies

Examples of special studies that should be considered include

- Investigating inactive oil and gas wells for groundwater monitoring.
- Investigating the behaviour of oil and gas chemical additives, geochemical tracers, and methane in groundwater
- Investigating potential contaminant pathways
- Investigating risk from well integrity failures
- Characterizing the role of aquitards in transport and vulnerability

Pilot and special studies are necessary to develop a credible and protective monitoring program

The need for ongoing data and program review

- **Periodically review and interpret data**
- **Develop an information management system**
  - —A georeferenced repository that is accessible to the public and water resources community
  - —All hydrogeologic, geologic, geophysical and chemical data and models generated by the regional, area, and neighbor monitoring programs
  - —Links to relevant information generated by other programs
- **Establish a Technical Advisory Committee**
  - —Provide a mechanism for adaptive management or "feedback"
  - —Review and assist in the design of special studies
  - —Evaluate components of the monitoring programs, including network design, analytes, frequency and duration of sampling

Data and program should be reviewed on an ongoing basis

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Contact and report information

Contact information

Bradley K. Esser, L-231
Environmental Radiochemistry Group Leader
Lawrence Livermore National Laboratory
Livermore, California
voice: 925/422-5247
email: bkesser@llnl.gov

Report information

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