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Considerations in Designing Statewide Programs to Monitor the Effects of Oil and Gas Development on Groundwater Resources

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California Senate Bill 4 of 2013 (SB4 – Pavley, statutes of 2013) mandates that the California State Water Resources Control Board (Water Board) develop and implement groundwater monitoring programs to assess and track the potential interactions between well stimulation methods designed to increase oil and gas reservoir permeability and groundwater resources suitable for beneficial uses. In California, well stimulation methods generally are being applied in areas that already have long histories of oil and gas development activities (**fig. 1a**). Consequently, it is very difficult to distinguish the effects of the new well stimulation activities without a more thorough understanding of the effects of other current activities associated with oil and gas development – and the legacy effects of past practices – and their potential to affect groundwater resources. The management task before the Water Board is to protect groundwater resources that are or may be used for beneficial uses from impairment by oil and gas development activities. The scientific task is to provide the Water Board with the information needed to manage existing and potential future risks to groundwater resources in a cost-effective manner.

Relatively little is known about the interaction between oil and gas development activities and groundwater resources in California. Conventional wisdom has held that oil and gas resources and groundwater resources suitable for beneficial use are sufficiently separated that interaction is unlikely, and therefore systematic groundwater monitoring has not been done. However, this assumption does not necessarily hold true in all oil and gas fields. The amount of separation (proximity) depends on the locations and the depths of the wells. The overlap between locations of wells used in oil and gas operations (**fig. 1a**) and locations of wells used for public and domestic drinking-water supplies (**fig. 1b**) indicates that in many parts of California, aquifers used for drinking-water supplies overlie or are adjacent to zones used for historic or current oil and gas development activities. A small sample of well log data for oil-related and water wells in two oil fields in Kern County (**fig. 2a**) illustrates two examples of the relation between the depths of wells used oil and gas development activities and the depths of wells used for water supply (**fig. 2b,c**). In both oil fields, there are wells used for irrigation and drinking water supplies that are located within approximately 1 mile of wells used for oil field waste injection or in which hydraulic fracture methods have been used. However, in the Kern River field (**fig. 2b**), the depth zones used for waste injection overlap the depths of groundwater resources used for irrigation and drinking water supplies; whereas, in the Rose field (**fig. 2c**), the zone in which hydraulic fracturing is being used for oil extraction is several thousand feet below the groundwater resources used for irrigation and drinking water supplies. A more complete mapping of the proximity in three dimensions of zones used for oil and gas development activities and groundwater resources currently used for irrigation and drinking water supplies will require compilation of data from Department of Water Resources (DWR) and Division of Oil, Gas, and Geothermal Resources (DOGGR) well-completion reports.

Most of these hundreds of thousands of well-completion reports currently exist only as scanned images of paper records.

As California's reliance on groundwater has increased, the extent of groundwater resources considered suitable for beneficial uses has expanded. Brackish groundwater is now used as a source in regional water supply portfolios (for example, by the San Diego Water Authority) and the recent drought is causing thousands of well owners to drill deeper. As a result, there is a potentially increasing the spatial overlap between oil and gas development activities and groundwater resources. The expanded usage of well stimulation technologies also has potentially increased this spatial overlap by enlarging the viable oil and gas production zones and increasing the intensity of oil and gas development activities. In addition, the U.S. Environmental Protection Agency has defined protected groundwater resources under the Safe Drinking Water Act as those containing less than 10,000 mg/L of total dissolved solids. Aquifer zones set aside for disposal of oil and gas waste are intended to exclude protected groundwater. The extent of groundwater meeting the federal criteria is poorly known in areas in and near oil and gas fields because efforts to map groundwater salinity generally have focused on defining the base of freshwater (water containing less than approximately 2,000 mg/L of total dissolved solids; for example, Page, 1986). In addition, hydrocarbon-bearing zones and other zones used for waste injection were defined as exempt from the Safe Drinking Water Act (Division of Oil, Gas, and Geothermal Resources, 1981); therefore, few groundwater quality data have been collected in those zones. Systematic mapping of groundwater resources in areas in and near oil and gas fields is needed so that the Water Board can make informed decisions about better defining the boundaries between protected groundwater resources and containment zones in which contamination of groundwater by oil and gas development activities shall be permitted, and about how to effectively monitor groundwater quality to ensure that these containment zones are maintained.

The degree of spatial overlap between zones used for oil and gas development activities and groundwater resources is just one of many factors that may affect the vulnerability of groundwater resources to contamination by oil and gas development (**fig. 3**). Fractures, natural or man-made, can increase the transport of fluids between oil and gas zones and groundwater resources, and low permeability layers can inhibit transport. Contamination of groundwater resources by flow of fluids along well boreholes located in oil and gas fields is a well-documented phenomenon (for example, Jackson and others, 2013). DOGGR currently regulates wellbore integrity, but with many oil and gas fields having wells drilled more than a century ago, and densities of active extraction, injection, and observation wells of up to 1,000 wells per square mile, the possibility of contamination via wellbores cannot be discounted.

Oil and gas companies have done detailed three-dimensional (3D) mapping of the geology of oil and gas zones (for example, Beeson and others, 2014) and similarly detailed 3D mapping has been done near the surface of the groundwater zones (for example, Faunt, 2009). These two types of 3D maps need to be linked to effectively show the spatial distribution and relationship of the two zones of interest. In addition, numerical groundwater flow models may be needed to simulate potential changes in groundwater flow patterns as a result of injection and extraction of fluids in oil and gas fields (including enhanced recovery and well stimulation techniques). Also, subsurface deformation may lead to

migration of contaminants out of the containment zones for contaminants associated with oil and gas development activities and into protected groundwater resources.

The concept of vulnerability is important for designing groundwater monitoring programs to assess and track the potential interactions between oil and gas development activities and groundwater resources suitable for beneficial uses. The concept supports development of a tiered study design in which areas where groundwater resources are less vulnerable are monitored with less intensity than areas where the resources are more vulnerable. In addition, vulnerability can change over time as a result of natural and anthropogenic factors, and a tiered study design can be adapted in response to those changes. The concept of vulnerability also provides a framework for understanding the processes by which oil and gas development activities may affect groundwater resources. This understanding is needed so that the Water Board can make informed decisions about what types of groundwater monitoring would be most appropriate under different conditions. For example, potential regional groundwater monitoring approaches could include using a statistical sampling approach similar to that used by the Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, or a representative style of monitoring similar to that used by agricultural coalitions in the Central Valley, or installation of a network of targeted monitoring wells. Different types of water-quality constituents and geochemical tracers may be more effective for detecting contamination resulting from different processes.

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Figure 1. (A) Locations of wells used in oil and gas development activities. Data from DOGGR list approximately 220,000 wells associated with oil and gas development activities as of July 2014. About half of these wells are listed as active extraction, injection, or observation wells. Hydraulic fracturing is reported in about 2,300 wells, mostly located in Kern County with lesser number reported in the Ventura, Los Angeles, and northern Sacramento basins. **(B)** Locations of wells used for drinking water supplies. Data from the Water Board's Division of Water Quality list approximately 18,000 active and standby wells used for public drinking water supplies. Wells used for domestic drinking water supplies are located over a wider areas than those used for public drinking water supplies [The number of domestic wells per 1-mile section was estimated by Johnson and Belitz (2014) using data compiled from DWR well completion reports.] Many of the areas with oil and gas development activities also are areas where groundwater is used for drinking water supplies.

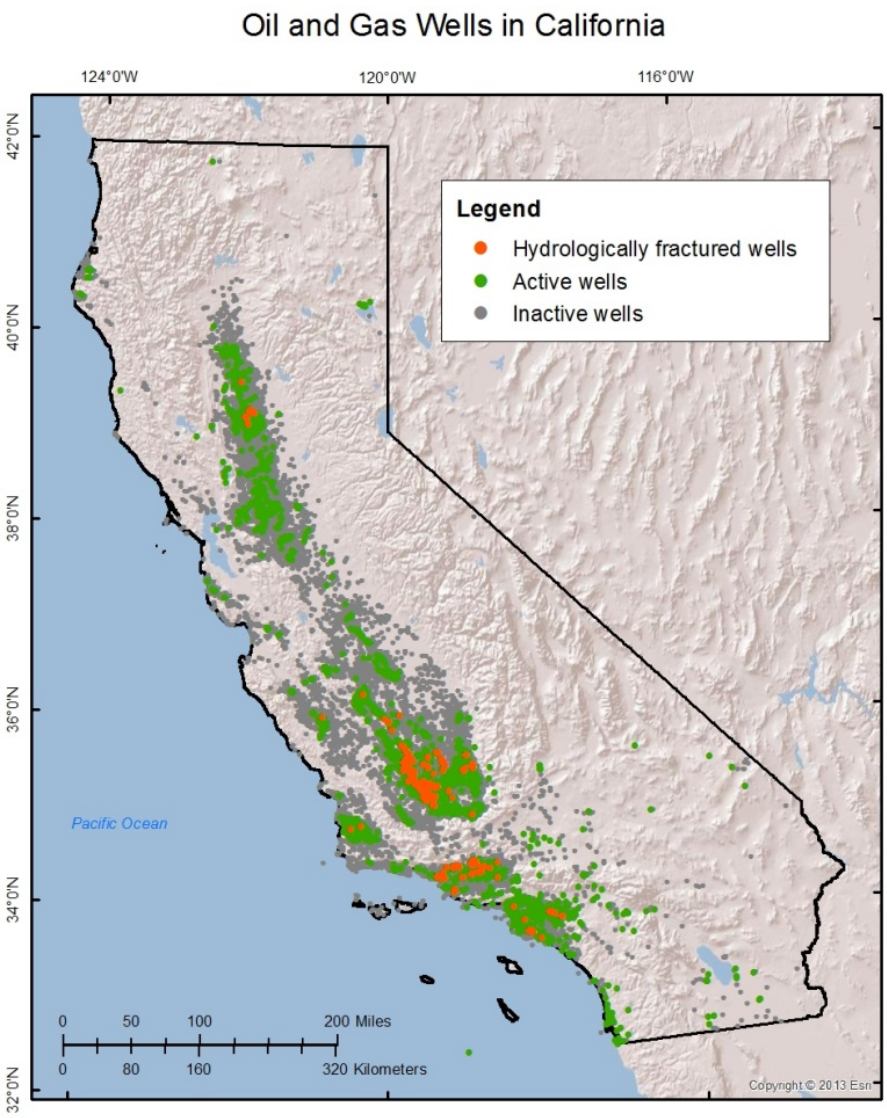


Figure 1a.

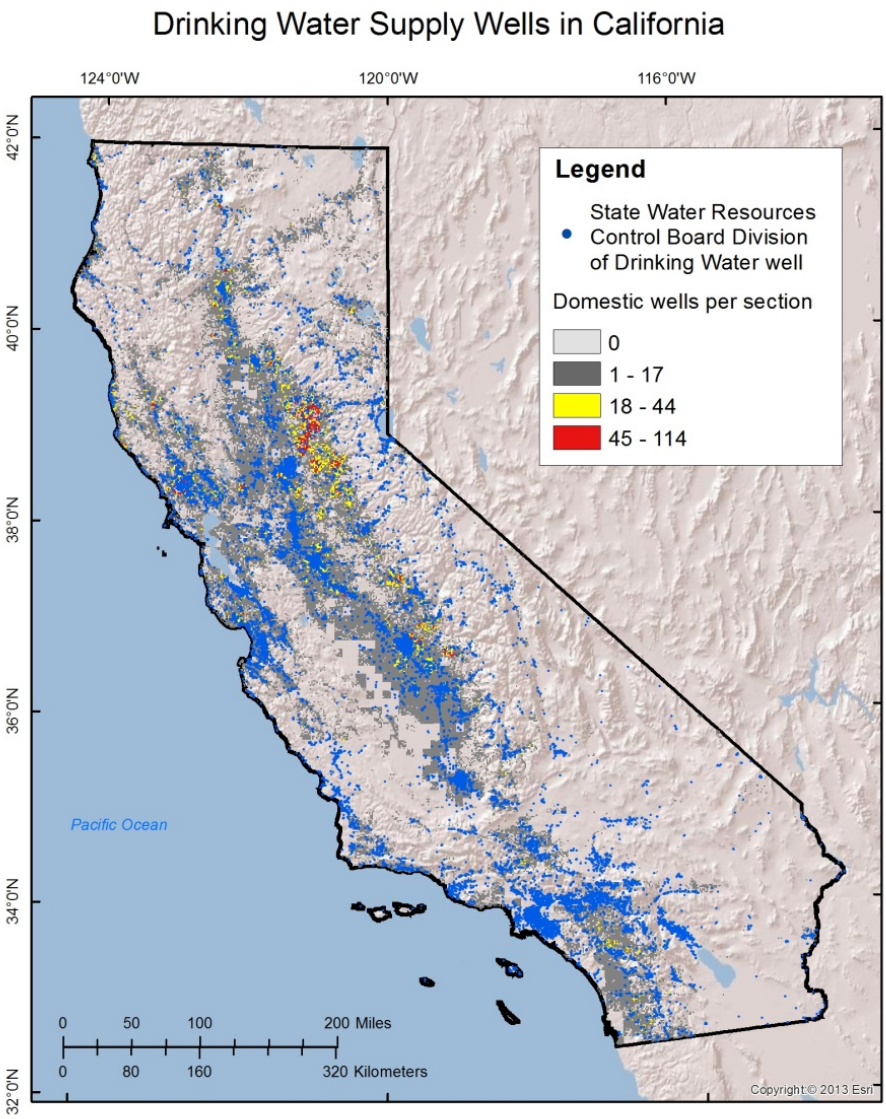

Drinking Water Supply Wells in California
124°0'W
120°0'W
116°0'W
42°0'N
40°0'N
38°0'N
36°0'N
34°0'N
32°0'N
Legend
State Water Resources Control Board Division of Drinking Water well
Domestic wells per section
0
1 - 17
18 - 44
45 - 114
Pacific Ocean
0 50 100 200 Miles
0 80 160 320 Kilometers
Copyright:© 2013 Esri

Figure 1b.

Figure 2. (a) Location of the Kern River and Rose Oil Fields

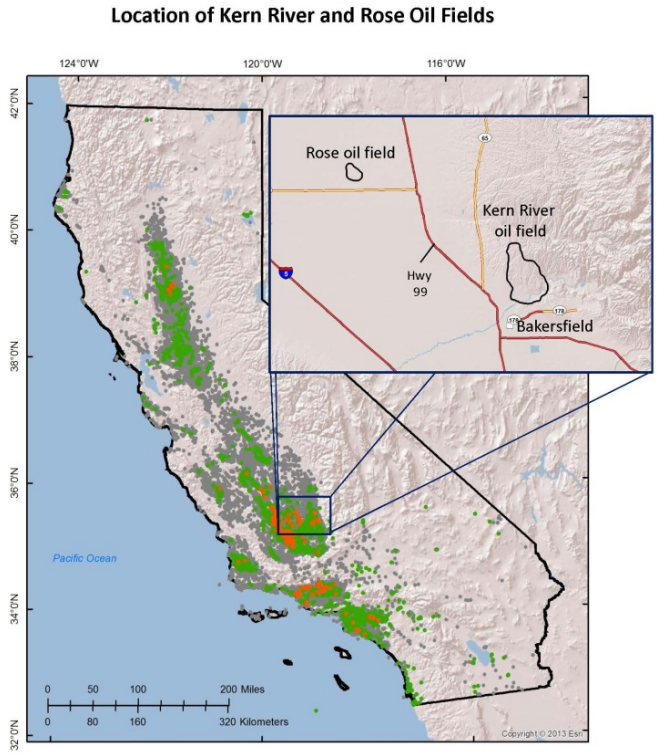


Figure 2a.

Figure 2. (b,c) In the Kern River oil field, most oil extraction wells (red) are less than 2,000 feet deep. The tops of the screened intervals in many of the injection wells used for waste disposal (yellow) also are less than 2,000 feet deep, and some are as shallow as about 600 feet deep. Irrigation, domestic, and public supply wells (blue) located within approximately 1 mile of waste injection wells are up to 1,500 feet deep. These data suggest that oil and gas development activities in the Kern River oil field may be occurring in relatively close proximity to groundwater resources suitable for beneficial use. **(B)** In the Rose oil field, oil extraction wells (red) are approximately 12,000 feet deep, and recent and proposed hydraulic fracturing activity (grey) is targeting a zone approximately 8,000 feet deep. Irrigation, domestic, and public supply wells (blue) located within approximately 1 mile of wells with hydraulic fracturing are up to 1,000 feet deep. These data suggest that the separation between oil and gas development activities and groundwater resources suitable for beneficial use is relatively large in the Rose oil field. [Data for depths of irrigation and drinking water wells obtained from DWR well completion reports, and data for depths of wells associated with the oil fields obtained from DOGGR. Note that currently, only about 15% of the wells shown in figure 1a have readily accessible depth information.]

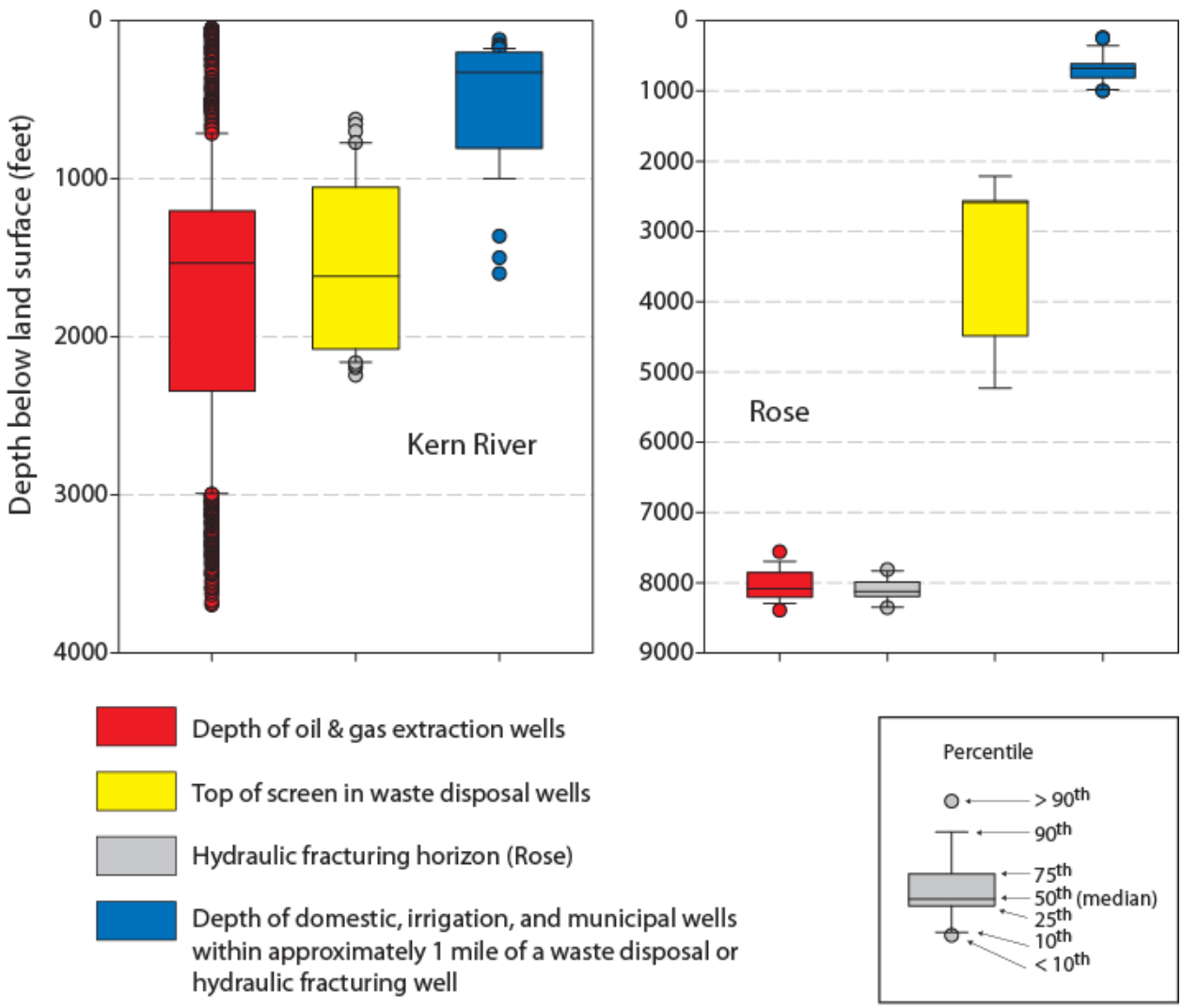
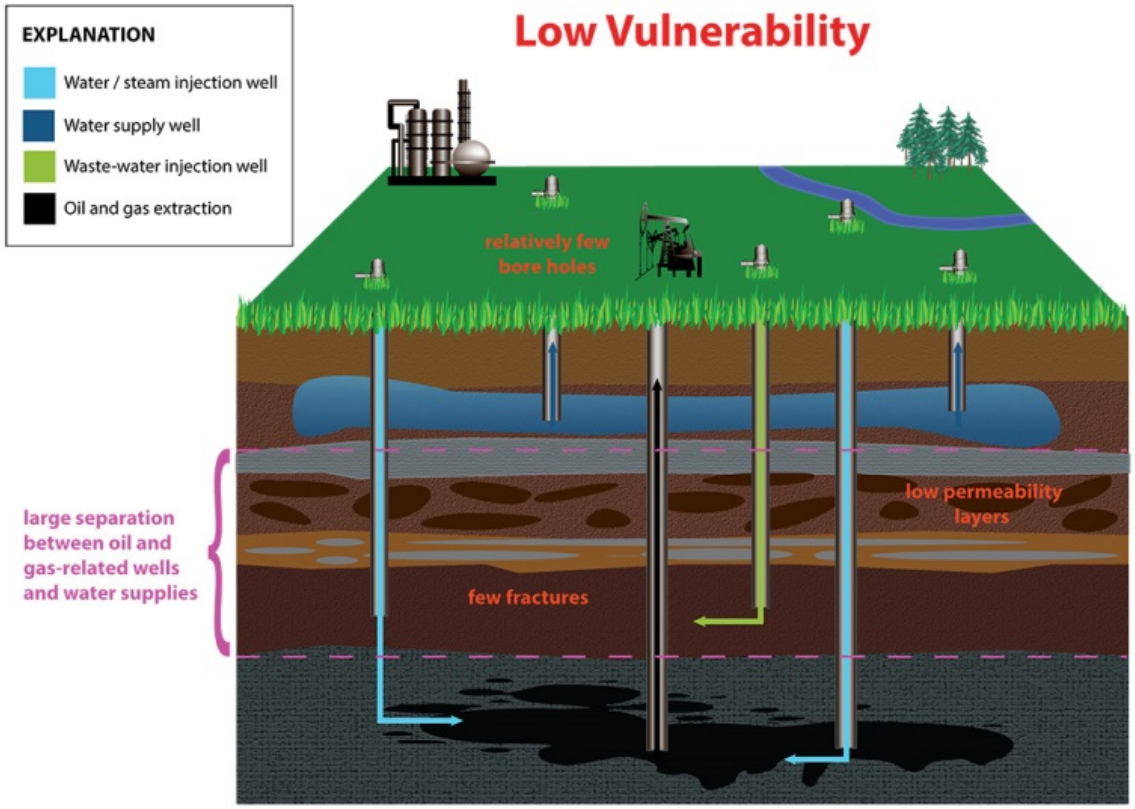
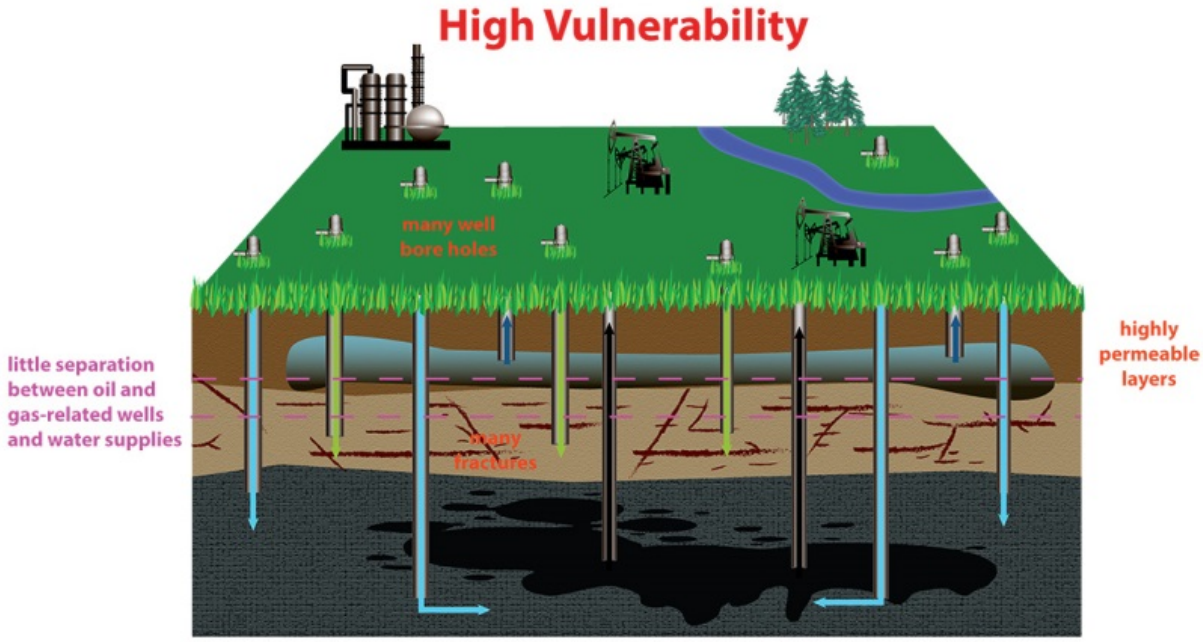


Figure 2b, 2c

Figure 3. (a,b) A conceptual diagram of a situation where groundwater resources have little vulnerability to contamination from oil and gas development activities is shown in the first block diagram. There is a large physical separation between hydrocarbon-producing areas and waste injection zones and portions of the aquifer being used for agricultural and drinking water supplies. The geologic formations in the zones separating the two resource types contain relatively few fractures and have low permeability. Finally, there are relatively few well bores which extend down into the hydrocarbon-producing and waste disposal zones. The second block diagram shows a situation where groundwater resources are highly vulnerable and the opposite conditions are all present.


EXPLANATION
Water / steam injection well
Water supply well
Waste-water injection well
Oil and gas extraction
Low Vulnerability
relatively few bore holes
low permeability layers
large separation between oil and gas-related wells and water supplies
few fractures


High Vulnerability
many well bore holes
highly permeable layers
little separation between oil and gas-related wells and water supplies
many fractures