The rapid growth in U.S. unconventional oil and gas has made energy more available and affordable globally but brought environmental concerns, especially related to water. We analyzed the water-related sustainability of energy extraction, focusing on: (a) meeting the rapidly rising water demand for hydraulic fracturing (HF) and (b) managing rapidly growing volumes of water co-produced with oil and gas (produced water, PW). We analyzed historical (2009–2017) HF water and PW volumes in ∼73 000 wells and projected future water volumes in major U.S. unconventional oil (semiarid regions) and gas (humid regions) plays. Results show a marked increase in HF water use, and depleting groundwater in some semiarid regions (e.g., by ≤58 ft [18 m]/year in Eagle Ford). PW from oil reservoirs (e.g., Permian) is ~15× higher than that from gas reservoirs (Marcellus). Water issues related to both HF water demand and PW supplies may be partially mitigated by closing the loop through reuse of PW for HF of new wells. However, projected PW volumes exceed HF water demand in semiarid Bakken (2.1×), Permian Midland (1.3×), and Delaware (3.7×) oil plays,
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Two key water issues associated with UOG resource extraction include:

(a) rising water demand for HF and

(b) managing high water volumes that are co-produced with oil and gas (produced water, PW, including flowback water from HF and water from subsurface formations).

A total of ~95,000 horizontal wells were registered in the United States for HF up through 2018 (Table S2). Increasing quantities of water used for HF, highest in the Permian Basin oil play,(6,7) have led to concerns about water scarcity, especially in the semiarid western United States, where the major unconventional oil plays are located.(8–10) HF has also been linked to another environmental problem, induced seismicity in some regions.(11,12)

Water is not only used, but also produced in large volumes from UOG reservoirs along with oil and natural gas, with the highest PW volumes recorded in the Permian. (6,13,14) The prevailing approach to PW management has been subsurface injection or disposal.(15–17) PW from UOG reservoirs cannot be injected into the shale or tight rock reservoirs because of low permeability; instead, the PW is mostly injected into nonreservoir geologic units. These injections modify subsurface fluid budgets and related pressures and may result in induced seismicity. Most recorded seismicity is linked to disposal near the basement and related to critically stressed faults, such as...
1.1. Hydraulic Fracturing Water and Produced Water Volumes

One of the big questions is whether increasing HF water demand may lead to water scarcity, increasing water stress in other sectors, particularly irrigation. UOG plays are found in areas with varying climate and hydrologic regimes. The major U.S. shale gas plays, the Marcellus, is in the humid eastern United States relying primarily on surface water for HF. Previous analysis indicates that streamflow was not negatively impacted by diversions for shale gas development.\(^{(28)}\) In contrast, tight oil reservoirs are found primarily in the semiarid western United States. Previous global analyses have highlighted potential water scarcity for UOG development in semiarid regions. However, many of those studies relied on global models restricting water resources to renewable surface water and groundwater supplies,\(^{(9,10)}\) whereas water users have been mining groundwater for irrigated agriculture for over a century, including major portions of the High Plains aquifer in the Permian Basin and the Carrizo Wilcox aquifer in the Eagle Ford play.\(^{(29,30)}\) Therefore, we suggest that water scarcity analysis in these systems needs to consider current and future water resource plans that include managed depletion in some aquifers.

Another major question is whether the rising volumes of PW may constrain UOG production because of induced seismicity concerns.\(^{(14,19,31)}\) The high levels of induced seismicity recorded in Oklahoma are attributed primarily to high PW disposal.