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Water Stress from High-Volume Hydraulic Fracturing Potentially Threatens Aquatic Biodiversity and Ecosystem Services in Arkansas, United States

Sally Entrekin,*,[†] Anne Trainor,[‡] James Saiers,[§] Lauren Patterson,[∥] Kelly Maloney,[⊥] Joseph Fargione,[#] Joseph Kiesecker,[▽] Sharon Baruch-Mordo,[▽] Katherine Konschnik,[○] Hannah Wiseman,[◆] Jean-Philippe Nicot,[^] and Joseph N. Ryan[¶]

[†]Department of Biology, University of Central Arkansas, 201 Donaghey Avenue, Conway, Arkansas 72035, United States

[‡]The Nature Conservancy, African Program, University of Cincinnati, 820G Rieveschl Hall, Cincinnati, Ohio 45220, United States

[§]School of Forestry and Environmental Studies, Yale University, 195 Prospect St., New Haven, Connecticut 06511, United States

[∥]Nicholas Institute for Environmental Policy Solutions at Duke University, 2111 Campus Drive, Durham North Carolina 27708, United States

[⊥]U.S. Geological Survey, Leetown Science Center, 11649 Leetown Road, Kearneysville, West Virginia 25430, United States

[#]The Nature Conservancy, 1101 West River Parkway, Suite 200, Minneapolis, Minnesota 55415, United States

[▽]The Nature Conservancy, Global Lands Team, 117 E. Mountain Avenue, Suite 201, Fort Collins, Colorado 80524, United States

[○]Environmental Policy Initiative, Harvard Law School, #4123 Wasserstein Hall, Cambridge, Massachusetts 02138, United States

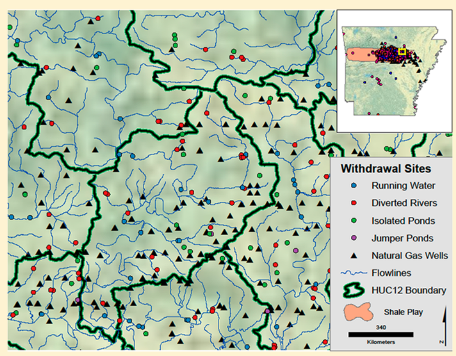
[◆]Florida State University College of Law, 424 West Jefferson Street, Tallahassee, Florida 32306, United States

[^]Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, 10100 Burnet Road, Building 130, Austin, Texas 78758, United States

[¶]Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, Boulder, Colorado 80309, United States

Supporting Information

ABSTRACT: Demand for high-volume, short duration water withdrawals could create water stress to aquatic organisms in Fayetteville Shale streams sourced for hydraulic fracturing fluids. We estimated potential water stress using permitted water withdrawal volumes and actual water withdrawals compared to monthly median, low, and high streamflows. Risk for biological stress was considered at 20% of long-term median and 10% of high- and low-flow thresholds. Future well build-out projections estimated potential for continued stress. Most water was permitted from small, free-flowing streams and "frack" ponds (dammed streams). Permitted 12-h pumping volumes exceeded median streamflow at 50% of withdrawal sites in June, when flows were low. Daily water usage, from operator disclosures, compared to median streamflow showed possible water stress in 7−51% of catchments from June−November, respectively. If 100% of produced water was recycled, per-well water use declined by 25%, reducing threshold exceedance by 10%. Future water stress was predicted to occur in fewer catchments important for drinking water and species of conservation concern due to the decline in new well installations and increased use of recycled water. Accessible and precise withdrawal and streamflow data are critical moving forward to assess and mitigate water stress in streams that experience high-volume withdrawals.



INTRODUCTION

In the United States, technological advancements, such as horizontal drilling in conjunction with hydraulic fracturing have spurred increases in unconventional energy development over the past decade. High-volume hydraulic fracturing (HVHF, often >4000 m^3 of fluid per horizontal well compared to <4000 m^3 for vertical wells and <400 m^3 for historical hydraulic fracture water use[1,2]) allows for the extraction of hydrocarbon resources by the high-pressure injection of fluids mixed with sand and chemical additives that fracture low-permeability rock and release the trapped hydrocarbons.[3,4] A median volume of 19 425 m^3 of freshwater per well is used to hydraulically fracture gas wells in the U.S., much of which is obtained by pumping freshwater from

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local streams.[5,6] There is potential for these withdrawals to cause water stress. Water stress can be quantified as either the risk of water scarcity for people that is caused by increases in economic costs and competition among uses[7] or as the extent and magnitude of altered natural streamflow that could result in loss of aquatic biodiversity and ecosystem function and services.[8,9]

As in most climatic humid regions, like Arkansas (AR), the risk of water stress from HVHF has been assumed to be low because only a small percentage of available water is used by humans. HVHF requires high volume withdrawals over short durations (one or 2 days); therefore, local stress could occur in streams and groundwater, particularly during periods of drought and high demand.[1,10,11] In the humid Marcellus Shale play region (which spans parts of Ohio, West Virginia, Pennsylvania, New York, and Maryland), small streams are a common water source for HVHF.[12] These small catchments are prone to water stress because streamflow is low compared to withdrawal rates. Consequently, catchments smaller than 675 km^2 in the Marcellus Shale play tend to be more at risk to water stress during drought in the absence of regulations that prohibit withdrawals during low-flow periods.[10,12,13] Meanwhile, arid regions are assumed to be at greater risk for water stress, although only catchments of areas <25 km^2, were identified as at-risk in the Upper Colorado River Watershed (UCRB), where underlying oil-and-gas bearing formations could be hydraulically fractured with relatively low volumes of water.[6,12] Despite the potential risk to biodiversity and human livelihood, spatial and temporal patterns of water stress from HVHF have yet to be assessed anywhere but the Eagle Ford shale play in Texas, UCRB, and Marcellus Shale play.[1,12]

Although headwaters (Strahler stream order first through third) provide drinking water for over 1/3 of the U.S. population and represent biodiversity hotspots, headwaters are particularly vulnerable to water withdrawals.[13,14] For example, in the south-central and eastern U.S., headwaters support a total of 34 federally listed endangered species that rely, in part, on streams, and 20 fully aquatic endangered species.[15] However, the extent to which HVHF water withdrawals are taken from small streams is poorly known. Moreover, headwater regulatory protection remains highly variable across the U.S., leaving streams in some areas vulnerable to substantial hydrologic alteration. Alterations could include impoundments that hold water for withdrawals.[16,17] With expanding high-density energy development, there is an urgency to assess potential impacts of HVHF development on streams.

Seasonal and annual variability in streamflow complicate headwater stream withdrawal regulations. To address this challenge in the Susquehanna River (SRB, 72% underlain by the Marcellus Shale play) The Nature Conservancy and the Susquehanna River Basin Commission (SRBC) assessed and then recommended daily variable water withdrawal thresholds to minimize impacts on aquatic communities and associated ecosystem services.[12,18,19] Although thresholds were for the eastern U.S., data used to generate withdrawal thresholds were compiled from published studies that can be applied when region-specific environmental flow relationships are unavailable. According to these recommendations, daily withdrawals should not reduce stream high flows by more than 10%. This withdrawal threshold was selected to prevent increasing sediment deposition that consolidates substrate, eliminates habitat for spawning, and clogs or smothers, gilled organisms. Furthermore, the recommendations guard against lowering median flows by more than 20% to avoid altering the regular function of aquatic species (e.g., growth and reproduction). Similarly, the recommendations would prevent withdrawals reducing low flows by more than 10% when elevated water temperatures and critically low dissolved oxygen already exist as threats to aquatic organisms.[18,20] Although biological withdrawal thresholds have been developed for the Susquehanna River Basin, these same SRB thresholds can be quantified from streamflow modeling to inform threat assessment and regulation in other states.[12,18,21] Studies that have measured have biological responses to altered streamflow are rare and have not been developed for streams in central AR. However, these generalized withdrawal thresholds provide an initial framework to gage potential biological stress.

Arkansas contains the Fayetteville Shale (FS) play, an active gas field, where freshwater and river systems support among the highest aquatic biological diversity in the U.S. Prior to widespread HVHF, consumptive demands for freshwater in central AR were relatively low.[22,23] As a response to widespread HVHF, water stress in this region was classified as "medium to high" suggesting that additional demands may contribute to water stress.[6,7]

Here, we quantified the potential for monthly water stress in running waters in the active FS gas field in central Arkansas. We used permitted water withdrawals in AR reported by the Arkansas Natural Resources Commission (ANRC). We also used water volume per well reported in FracFocus[24] to assess HVHF daily water usage compared to withdrawal thresholds based on modeled streamflow. FracFocus is a nonregulatory national hydraulic fracturing chemical registry. First, we summarized the State's nonriparian permits to assess where, when, and how much water was permitted for HVHF. Second, we asked whether estimated daily water usage, to date, could reach withdrawal thresholds that may have effects on aquatic organisms. We then extended this analysis to forecast HVHF withdrawals and associated impacts through 2030. Finally, we compared factors that may contribute to water stress in AR to similar water stress metrics for streams in the SRB where monitoring and data review are used to update regulations to reduce effects from HVHF. We compare AR to the SRB because AR represents a more typical permitting process for riparian-rights states,[25] with some deviations, while the SRB is regulated by an unique interstate commission (SRBC) that coordinates with the federal government through the SRB compact that was adopted by the U.S. Congress in the 1970s.[19]

MATERIALS AND METHODS

Overall Analytical Approach. First, we examined water sources permitted for withdrawals and peak permitted instantaneous withdrawal rates. Instantaneous rates were scaled to their logical daily limit as a way to compare streamwater volumes represented as exceedance probabilities of P_{90} (low flow: 90% of the time flow is predicted to exceeded this value), P_{50} (median flow: 50% of the time flow is predicted to exceeded this value), and P_{10} (high flow: 10% of the time flow is predicted to exceeded this value). Because there are no daily limits, our estimates from peak instantaneous withdrawals rates are worst-case scenarios. We compared daily peak permitted limits to streamflow in June, when flows tend to be lower but regression models are still relatively robust, to explore the possibility of water stress. We calculated daily water usage by gas operators for catchments (rather than withdrawal locations) represented at the smallest standardized hydrologic unit codes (HUC12, HUC10, and HUC8) because water usage at an individual well could not be linked to the permitted withdrawal site. Catchments ranged in size from 47 to 1959 km^2. Daily water usages for each catchment were then compared to modeled stream high (P_{90}), median (P_{50}), and low (P_{10}) flow SRB withdrawal thresholds for each catchment in the FS.

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These withdrawal thresholds are defined as modeled flows at ≤10% of low flow (P_{90}), ≤ 20% of median flow (P_{50}), and ≤10% of high flow (P_{10}). In the SRB, similar withdrawal thresholds are used to define pass-by values (i.e., withdrawal restrictions when mean annual streamflows fall below these values). Then, daily water usages were calculated from projected well densities and their associated per well water usage within the same catchment, summed and the sum was divided by catchment streamflow high, median, and low flow exceedance probabilities as an index of Surface Use Intensity as a daily water usage (SUI_{dwu}). SUI_{dwus} were projected up to the year 2030 using well build-out projections based on Browning et al.[57]

Modeling Streamflow on Free-Flowing Streams. Because most of the withdrawal locations in AR were on streams without flow data, we first estimated daily flow for each withdrawal location based on stream and catchment characteristics using weighted least-squares regression models.[26−28] We delineated catchment areas from the National Hydrography Data set (NHD) in ArcGIS 10.2.2 with ArcHydro tools extension (ESRI), and computed physical and climate predictor variables within the delineated permitted withdrawal catchments and HUC8, HUC10, and HUC12 catchments (see the Supporting Information, SI, Section A, Table S1). Modeled daily streamflow was used to calculate high (P_{90}), median (P_{50}), and low flow statistics (P_{10}, Table S2).

Water Withdrawal Permit Locations. Water withdrawn and transported to another location requires nonriparian permits in AR.[29] We acquired the ANRC nonriparian permits database in July 2015. Although the AR Water Plan Update from 2014 or 2016 rule is not reflected in our research, the updates do not change our conclusions. The main update was to add excess surface water estimates for all AR river basins.[30,31] The ANRC permits withdrawals when the total cumulative withdrawals in a catchment (estimated at the HUC12) do not exceed the catchment's annual yield and the cumulative withdrawals in a catchment do not exceed 25% of the estimated excess of the annual yield in the larger HUC8.[30] The ANRC estimates excess from projected consumptive uses, precipitation, and in-stream minimum flows required for aquatic organisms at the HUC8 level. Therefore, permitting procedures are most protective of small HUC12s nested within a larger HUC8 compared to those at the top of a catchment that have lower streamflow.[32] Permits are issued at 5-year intervals. We used withdrawal permit location proximity to high-resolution National Hydrography Data set of flowlines to verify the classification of the withdrawal source.

Peak Permitted Instantaneous Withdrawal Rate Compared to Catchment Size and Scaled to 12- and 24-h Permit Volumes. Daily streamflow was estimated as high, median, and low flow from regression models because gage data were not available for our selected catchments (see Regression Equations SI, section A, Table S2).[10,12] Permits specified a peak instantaneous withdrawal rate, as measured in m^3/s, which we scaled to a peak, permitted 12 h and daily rate by assuming the instantaneous withdrawal rate was sustained. We expect that, in most cases, withdrawals occurred over some (unknown) fraction of the day and hence the peak permitted withdrawal rates used here are considered "worst-case scenarios" and likely exceed actual withdrawal rates. We then compared the maximum 12- and 24-h permitted withdrawals to modeled June high, median, and low streamflows. We selected June as an example of a relatively dry month that also had robust streamflow prediction models. The utility of this analysis is to identify potential for water stress and characterize withdrawals sites and times when lower peak-permitting values may be more protective.

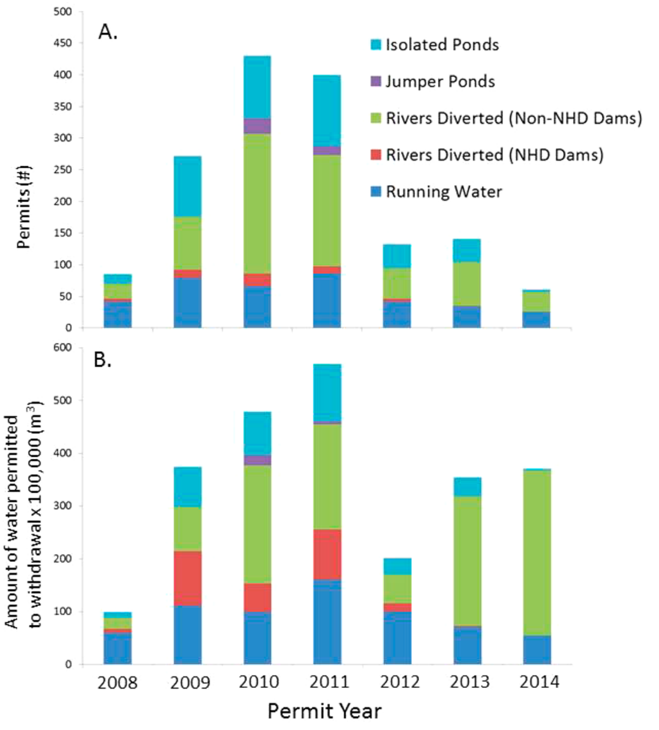

Figure 1. Arkansas Natural Resource nonriparian surface water withdrawal permits. (A) Permit number for each permit site and (B) water volume permitted to be withdrawn each year. Rivers diverted (non-NHD Dam) are streams with small dams (<7.6 m), but the dam falls below the threshold requiring a Dam Safety Permit. The withdrawal site does not correlate to a recorded dam location in the NHD data layer. Rivers Diverted (NHD Dam) are streams with dams at or above the threshold requiring a Dam Safety Permit. The withdrawal site does correlate to a recorded dam location in the NHD data layer. Running Water indicates a stream withdrawal site from the stream bank with no pond.

Daily Water Usage for HVHF. Arkansas requires annual estimated withdrawal reports for each permittee as hard-copy documents that are currently not publically available. Permittees are not required to meter withdrawals;[29] therefore, actual usage for a withdrawal site is unknown. We supplemented the permitted withdrawal data with data on actual water usage at the catchment scale (see SI, section B, Figure S1) available from FracFocus where operators voluntarily report withdrawals. Although the water-withdrawal site for each well is not systematically reported, gas-well locations are known, and we assumed the water withdrawal occurred within the same catchment.[33] Daily water usage was calculated as the number of well completions per month in a catchment times the median estimated water used per completion divided by days in a month (see SI, section B, eq 1). We also calculated daily water usage by assuming 100% recycling of flowback/produced water, which could result in a 15−25% reduction in water used per well completion.[34] The amount of water recycled depends on the chemical composition, amount and timing of produced water that will require additional freshwater for reuse.[5,14] Since 2008, between 50 and 70% of wells were fractured with recycled produced water that represents an average of 15% of fluid used in the fracturing process.[5] We likely overestimated the amount of recycled water used in our analysis because we were unable to associate the amount of recycled water to individual wells.

We evaluated withdrawals against the three SRB withdrawal thresholds.[18] We compared daily water usage with and without

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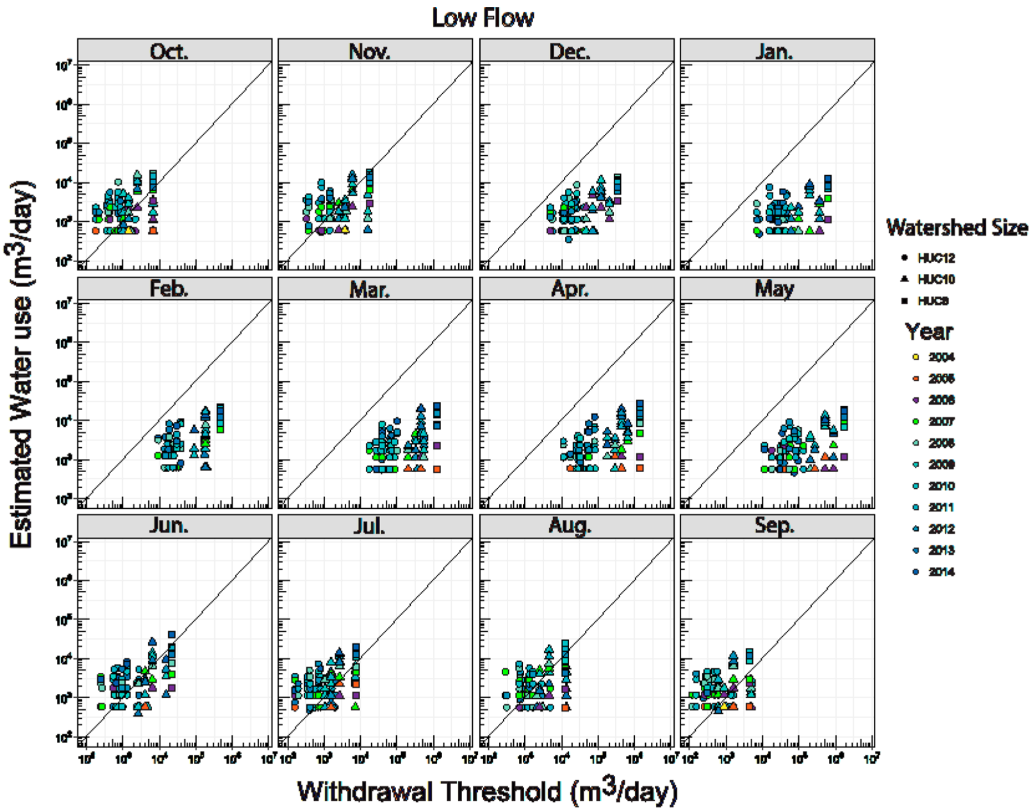

Figure 2. Monthly estimated daily water usage by low flow biological withdrawal thresholds calculated as 10% below the 90% flow exceedance value (P_{90}).[18] The 1:1 line is where daily water usage is equal to the withdrawal threshold. Values above this line serve as a general indicator of potential for biological stress and were based on expert opinion and not scientific studies from Arkansas. The number of points differs across months based on the location of well completions (*N* ranges from 95 to 104).

recycled produced water to withdrawal thresholds to identify the months and flow regimes that are most likely to exhibit water stress for biota.

Current and Future Shale Gas Risk to Biodiversity and Ecosystem Services across HUC12 Catchments. In addition to estimating water usage for recent years, we evaluated the potential impact of water use due to future HVHF development on biodiversity and drinking water in the region by using published natural gas build-out scenarios (see SI, section C for detailed methods, Figure S2). To illustrate the seasonal and spatial shift in potential water stress, we computed and mapped the ratio of daily water usage by stream low- and median-flow statistics and reported them as surface use intensity indices (SUI_{dwu}). July and March represent a dry and wet month based on average monthly precipitation and regression rigor, respectively (see SI, section B, eq 2). To demonstrate the shift in water stress across years, we compared these SUI_{dwus} (high, median, and low during wet and dry months) for three years: (1) the year with the most well completions (2009), (2) midpoint in the buildout scenario (2019), and (3) the final buildout scenario year (2030). The spatial and temporal shifts in SUI_{dwu} were compared to key environmental and social features in the region to evaluate the future possible water stress on ecological and human interests. To identify where water stress overlapped with areas important for biodiversity, we used the number of species of conservation concern. To identify where water stress impacts overlapped with areas important for drinking water provision, we used the drinking water importance index from the U.S. Forest Service's Forests to Faucets data set[35] and 2012 human population in each HUC.[36]

RESULTS AND DISCUSSION

High-Density, Unconventional Oil and Gas Development Used a Total of 2.8 × 10^7 m^3 of Freshwater from 2004 to 2014. The active gas field of the FS covers an area of 22 900 km^2 and contains 5207 gas wells that have been completed by HVHF since 2004 (Arkansas Oil and Gas Commission website). Well completions per year ranged from 7 in 2004 to a maximum of 898 in 2009. Completions occurred throughout the year, at a similar rate regardless of season (Figures S3A and S3B). In 2010, for example, monthly completions peaked at 90 in July when median streamflows were low but, in 2013, peaked in March, when median streamflows were comparatively high (Figure S3B). Of all AR gas wells, voluntary disclosures of per well water usage to FracFocus increased from 9% in 2012 to 83% in 2014. Median water usage per well equaled 17 707 m^3, while the 25th percentile and 75th percentiles were 14 386–21 305 m^3.[3,37–39]

Regression Models Better Predicted Median and High Streamflow. Monthly high, median, and low-flow statistics could be quantified by two to six predictor variables that typically predict flow in other regions (Table S2). According to the monthly flow statistics, most of the monthly regression models suggest that streamflows (P_{90}, P_{50}, and P_{10}) were positively associated with catchment area (Table S2). During the dry season (June–October), percent forest cover was a positive land use predictor for all three streamflow rates (P_{90}, P_{50}, and P_{10}). Median (P_{50}) and low (P_{90}) streamflows during the wetter months (November–April) were positively associated with monthly precipitation. High flows (P_{10}) were positively associated with precipitation for both dry and wet season months (Table S2). Calculations of adjusted

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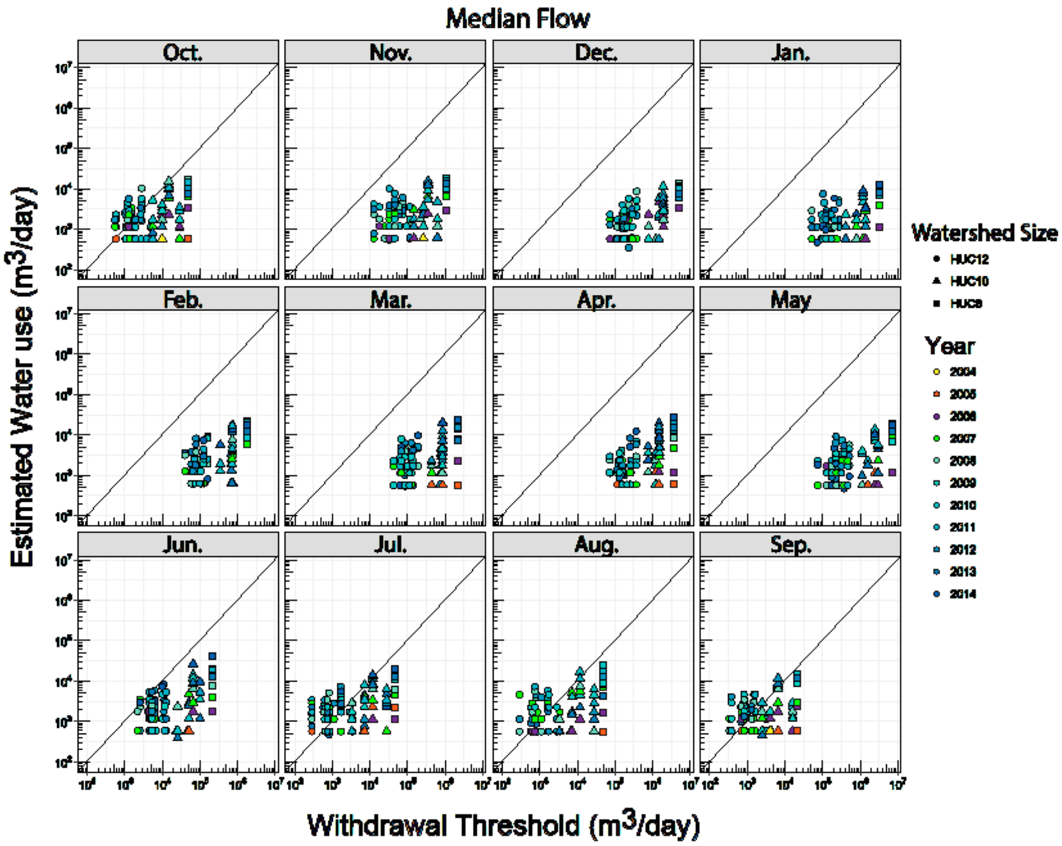

Figure 3. Monthly estimated daily water usage by median flow biological withdrawal thresholds calculated as 20% below the 50% flow exceedance values (P_{50}).[18] The 1:1 line is where daily water usage is equal to the withdrawal threshold. Values above this line serve as a general indicator of potential for biological stress and were based on expert opinion and not scientific studies from Arkansas. The number of points differs across months based on the location of well completions (*N* ranges from 95 to 104).

r-squared values ranged from 0.41 to 0.96 and tended to be greater for high and median flows. High flow regression models performed the best with more narrow confidence intervals and *r*-squared values ≥0.83, while models for median flow in the drier months were as low as 0.57 in September (Tables S2 and S3). Low flow regression models also performed less well for drier months that had more days with zero values, with r-squared values ranging from 0.41 to 0.84. Model uncertainty points to the need for more gaged streams and an acknowledgment of uncertainty in streamflow exceedance probabilities that are common in low-flow regression models (Table S3).

Eighty-Four Percent of HVHF Water Was Permitted for Withdrawal from First to Third Order Streams. In AR, 1521 nonriparian permits to withdraw water for HVHF were granted between 2000 and 2014, with the number of permits increasing from an average of less than 30 permits per year (prior to 2008) to 304 a year (2009−2014). In contrast, Pennsylvania Department of Environmental Protection (PADEP) and the SRBC issued 297 HVHF withdrawal permits in Pennsylvania (PA) between 2000 and 2014.[10,12] Overall, 71% of all AR permitted locations were running water (25%) and dammed streams (46%). The remaining 29% of permits were for isolated ponds. Fifty-nine percent of the permitted sites were located on first order streams, and 84% were located on third order or smaller streams in AR (Table S4) compared to 22% of sites on similarly small streams in PA.[10] In AR, fifty-two percent of permit sites on first to third order streams were without dams (i.e., running water) and 15% of those dry at some point during the year (i.e., intermittent). Running waters comprised ∼50% of the total permits in 2012, while dammed streams supported the majority of permits in 2013 and 2014 (Figure 1A). Of the 236 dams located in the producing portion of the gas field, 153 were coded by the Army Corp of Engineers as likely built to hold water for hydraulic fracturing (FOIA No. 15-030399). Ninety-seven percent of dammed streams were first through third order, and 34% of those were intermittent. Seventy-three percent of HUC12s in the active gas field (52 of 72 total) had dams installed for HVHF. Linear stream distance upstream of the new dams was 445 km (3.2%) of total stream length in the FS active region.

Permitted peak daily withdrawals ranged from 489 to 574 946 m^3 (median = 29 359 m^3) with a maximum total annual volume from 4933 to 986 784 m^3 per site. The upper withdrawal volumes were permitted for larger rivers. The ANRC permitted the highest peak daily water withdrawals between 2009 and 2011 (range: 4×10^7 to 6×10^7 m^3), coinciding with peak gas-well drilling and HVHF (Figure S3B). In comparison, the PADEP and the SRBC permitted between 54 and 18 314 m^3 per day with a median of 2663 m^3.[10] ANRC permitted more water from the smaller dammed and intermittent streams during peak hydraulic fracturing years (2009−2011) than other sources (Figure 1B). It appears that dammed streams were permitted at higher withdrawal rates. For reference, although regionally variable, first order streams in north-central AR have streamflows ranging from median values of about 20 000−40 000 m^3 per day.[40] Although the number of permits issued from 2012 to 2014 declined, the amount of water permitted was still relatively high, suggesting fewer permitted sites, mostly on dammed streams, with more water permitted to withdrawal per site (Figure 1). Off-site water

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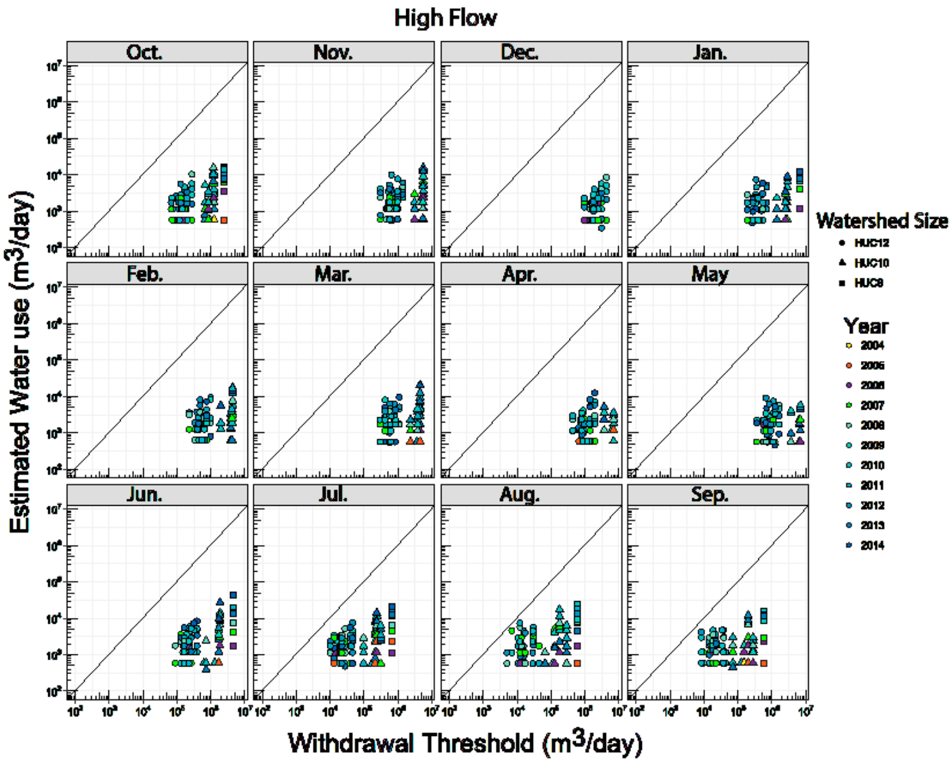

Figure 4. Monthly estimated daily water usage by high flow biological withdrawal thresholds calculated as 10% below the 10% high flow exceedance values (P_{10}).[18] The 1:1 line is where daily water usage is equal to the withdrawal threshold. Values above this line serve as a general indicator of potential for biological stress and were based on expert opinion and not scientific studies from Arkansas. The number of points differs across months based on the location of well completions (N ranges from 95 to 104).

storage and impounded or dammed streams may have been the primary water source of HVHF water during dry periods because 25% of the permitted withdrawal sites were intermittent streams. Impoundments can dampen downstream high flows and increase low flows that change habitat for fish and other aquatic species.[41] Small dams increase nutrient resident times and water temperatures that, in combination, support conditions for a few productive algal species to bloom and become harmful to livestock and people.[42,43] A more comprehensive analysis of hydrologic, biogeochemical and ecological connections among off-site water storage ponds, dams, and headwater streams is needed to fully understand risk from HVHF.[44−46]

Permitted Water Withdrawals Did not Relate to Withdrawal Location Catchment Size. Of the 376 permits on running water, 53% were from streams mostly with catchments less than 150 km^2 (Figure S4A). Permitted volume did not relate to catchment size (Figure S4B) in AR or permit sites in the Marcellus Shale play.[10,41] Arkansas issued 64% more withdrawal permits on small streams (1st through 3rd Strahler-Order) compared to PADEP and SRBC combined.[10] Daily permitted withdrawals in AR were 1 order of magnitude greater (489 to 574 946 m^3/d; median = 29 359 m^3/d) than daily permitted withdrawals in the SRB and Ohio River Basin (ORB) (range: 50 to 18 000 m^3/d; median = 2663 m^3/d[7,11]). The SRBC caps daily withdrawal rates at 25 000 m^3 per day.[11] High permit volumes relative to water availability suggest a potential disconnect between the amount of available water and withdrawals limits that highlight the need for ecologically defined thresholds.

When instantaneous withdrawals were taken to their logical daily maximum, they could exceed streamflow median- and low-flows. For example, from 2004 to 2014 in June, 65% (95% CI range 59−72%) of permit sites had maximum daily withdrawals that could exceed median streamflow, while 92% (95% CI range 90−92%) of permit sites had maximum daily withdrawals that could exceed low flow. If operators pumped water for 12 h, then projected exceedances at median flow were 50% (95% CI range 48−55%) of withdrawal sites at median flow and 88% (95% CI range 79−90%) of the sites at low flow. Because modeled median streamflows in June were low in many withdrawal locations (median flow = 11 935 m^3/d), pumping rates of 0.33 m^3/s (a common peak instantaneous rate) could be sustained for 9 h. Exceedance likely did not occur because state regulators were on the ground to prevent water stress, and operator withdrawals totaled only 35% of the permitted water. Arkansas does not set systematic pass-by flow requirements; however, if the water level reaches the ANRC-defined "red zone" as that indicates regional water shortages then nonriparian users are the first to lose withdrawal rights.[30] To date, the red zone has not been reached and the ANRC has not had to temporarily stop withdrawals. Our analysis points to risk associated with peak instantaneous withdrawal limits without daily withdrawal limits scaled to the daily amount of water available at the source. Daily peak permitted withdrawals exceeded daily low flows at about 14 withdrawal locations across the ORB and SRB; however, maximum withdrawal rates were typically not realized, pass-by flow requirements prohibited withdrawals from most small streams during low-flow periods, and metered withdrawals did not exceed the recommended streamflow thresholds.[10,47]

Daily Water Usage May Exceed Withdrawal Thresholds. Average daily water usage was estimated to range from 346 to 442 186 m^3 from 2011 to 2014 across our selected catchments. Under our low flow predictions and without accounting for recycled water, withdrawal thresholds could be exceeded in 48−79% (95% CI range 24−35%) of the catchments during the driest months (June−November, Figure 2). When 100% use of recycled water was assumed, withdrawal thresholds were exceeded in 48−69% (June−November) of catchments. Estimated daily water usage could exceed withdrawal thresholds in 7−51% (95% CI range 9−21%) of the catchments from June through October at median flow; accounting for recycled water reduced the range to 3−45% (Figure 3). Estimated daily water usage never exceeded high-flow withdrawal thresholds (Figure 4).

Biological effects from reduced flow are uncertain because environmental flow-biota relationships are lacking and our modeled streamflows had significant uncertainty, particularly during low flow periods.[48] Further, thresholds used here are based on expert opinion and were developed for perennial and not intermittent streams. Still, our analysis highlights data gaps, and generalizations can be made based on past studies to inform needed studies. For example, although daily water usage did not exceed withdrawal thresholds in spring and winter, when most AR fishes usually spawn and high flows transport sediment downstream, usage was predicted to have exceeded withdrawal thresholds at low and median flows in autumn when insect oviposition and recruitment of headwater insect species is greatest and some fishes spawn.[49] Altering streamwater levels affects stream temperatures and further reduces habitat quality, resulting in additional reductions in oviposition sites that can alter aquatic insect emergence patterns, affecting riparian food webs.[50−52] Sessile and sedentary organisms, like mussels, are particularly vulnerable to local extirpation from stream bed drying during drought, even in the absence of anthropogenic water withdrawals.[53] In total, episodic streamflow changes from withdrawals could degrade water quality by reducing the population density of some taxonomic groups, eliminating species most sensitive to changes in water levels, and cumulatively altering biological communities that assimilate nutrients.[54,55]

Future Build-Out Models Can Be Used to Avoid, Minimize, or Mitigate Risk of Water Stress. We compared SUI_{dwu} in dry (July) and wet (March) months for 2009 to corresponding estimates of SUI_{dwu} made under shale-gas build-out projections for 2019 and 2030. An SUI_{dwu} greater than one indicates that HVHF water withdrawals within a catchment could exceed the median flow for that catchment (i.e., indicating possible stress). As in 2009, projected SUI_{dwu} in 2019 and 2030 were less than one at median streamflows in all HVHF-active catchments in March (Figure 5). However, in July, more catchments have experienced severe water stress in 2009 ($n = 4$) than is projected for 2019 ($n = 1$) and 2030 ($n = 1$) resulting from more well completions through 2009 compared to projected build-out (Figure 5). SUI_{dwu} varied less in space than across years because build-out was projected to remain concentrated in the more productive gas field region. This projected expansion of drilling could overlap with areas important for drinking water provision (44−84 surface water importance scores across HUC12s out of a possible 100 based on Forest Services Forest to Faucets scoring system[35]) and species of conservation concern (one catchment with 3−4 aquatic species of conservation concern). Although fish and insect population relationships to streamflow have not been established in these streams, they have in other regions[56] and understanding overlap and possible conflict among water users could provide impetus for regional analyses. Past and projected daily water usage occurred in catchments that support drinking water for surrounding cities with as many as 63 000 people and up to 10 aquatic species of conservation concern (Figure 5). Assuming 25% lower water usage per well to account for recycling did not change projections; however, model uncertainty occurred

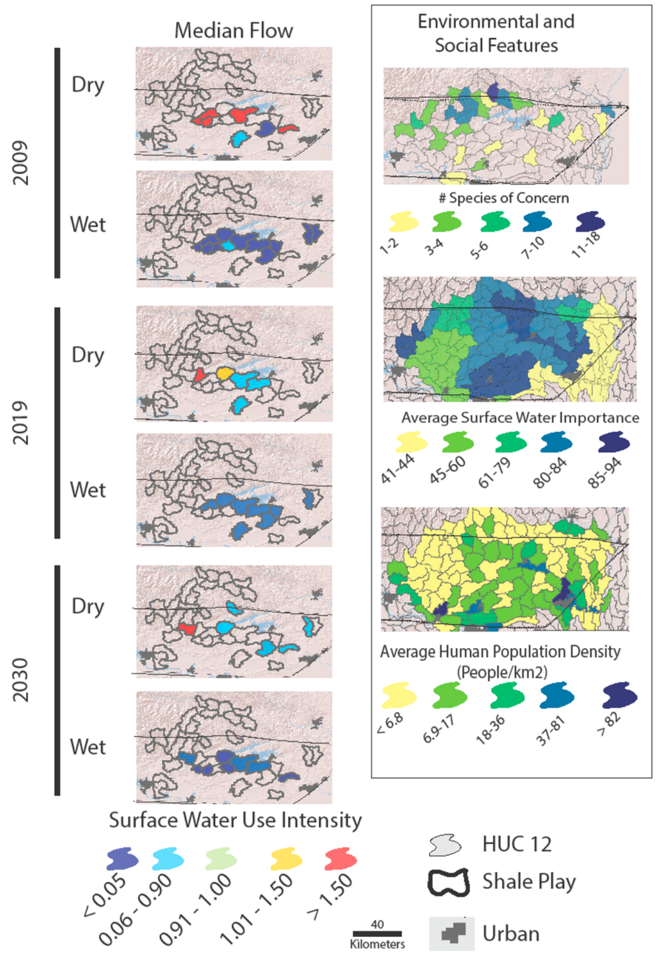

Figure 5. Daily average water usage was divided by median flow as a representation of Surface Use Intensity daily average usage (SUI_{dwu}) in July (a representative dry) and March (a representative wet) in a year with the a high number of well completions (2009) compared to predicted SUI_{dwu} modeled from build-out scenarios in the FS. SUI_{dwu} was not calculated for catchments (shown as gray polygons) if the buildout scenario did not predict well completions for that specific time stamp. SUI_{dwu} can be compared with other water uses such as average surface water importance based on surface drinking water intake locations and population and mean annual water supply,[35] aquatic species of conservation concern, and human population within HUC12s. All catchments under Environmental and Social Features were highlighted if SUI_{dwu} were ≥1.

from median well water usage volumes disclosed in FracFocus and streamflow regression models.

In general, water stress was predicted to be less severe and occur in fewer catchments in the future from fewer HVHF wells and increased use of recycled water, both of which reduces the need for locally sourced freshwater withdrawals.[5,57] Notably, based on our model calculations, withdrawals required for just one well completion were sufficient to cause streamflow reductions that exceeded low- and median-flows in small streams during the drier months. Our analysis could be used to improve decisions on withdrawal permit siting by identifying streams at high risk to changes in their hydrologic regime and associated uses. For example, catchments with the most productive shale gas reserves, but that also serve the most people and have the most sensitive aquatic organisms, can be flagged for additional assessment and planning prior to permitting withdrawals to minimize impacts from infrastructure on resident organisms[58] (Figure 4).

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Regulatory Modifications Could Reduce Risk of Water Stress. Adaptive management practices to conserve water resources will be particularly important as AR is predicted to experience fewer but higher magnitude rain storms and drier summers, which may exacerbate HVHF-related water stress.[59] Seasonal water harvesting during peak flows is becoming more common in water-stressed regions, like Arkansas' Mississippi River Alluvial Plain, where the State has incorporated storage reservoirs into the State Water Plan (2014). Off-site water storage facilities may be a more reliable and ecologically sound practice than stream impoundments, and the SRBC has also encouraged this practice.[35] The SRBC and other PA jurisdictions have also taken steps to encourage recycling of acid mine drainage or natural gas produced water to reduce demand for freshwater.[13] In addition, the SRBC has adopted several policies to avoid water stress, which could be considered in other shale plays where HVHF is expanding:[35] established permitted locations, maximum daily pumping volume scaled to stream size, habitat loss caps of 5−10% per permit depending on the stream reach characteristics, maximum operational pumping rates to protect aquatic species on site, low-flow pass-by levels to protect aquatic life, gages that trigger pass-by levels, real-time flow status in relation to pass-by levels with remote access, and operator withdrawal disclosures submitted as standardized, digital form to integrate with a larger databse. In addition, starting in 2012, the SRBC began considering the cumulative effects of all withdrawal permits.[35] Modified state regulations that incorporate key features of SRBC policy such as tailoring permit volumes to stream size, setting maximum daily withdrawals, and identifying ecologically meaningful minimum daily pass-by flow requirements could further reduce the potential for water stress and permit-specific oversight. The SRBC regulations that incorporate these features may serve as examples for regulators in other shale plays.[60,61]

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b03304.

> Additional analysis that supports potential for water stress in AR streams that were from state permitting agency, modeled streamflow, and estimates of water usage by gas operators for hydraulic fracturing are provided in the supporting information (SI). Table S1 are landscape variables used to develop streamflow statistical models. Table S2 are monthly streamflow regression models calculated for low (P90), high (P10), and median (P50) flow exceedance for ungaged streams. Table S3 are estimated streamflow, upper and lower 95% confidence intervals from the regression equations for each hydrologic unit code (HUC8,10, 12) appended at the end of the SI. Table S4. are water withdrawal nonriparian permit sites summarized by water source. Figure S1 are catchments at the Hydrologic Unit Codes 12, 10 and 8. The Browning et al. 2014 tier map and tier levels are illustrated in Figure S2. Figure S3 are the (A) number of well completions (bars) using HVHF and total volume of water used (dashed line) and (B) the number of well completions in each month and completion years from 2009 to 2013 in the Fayetteville Shale play. Shaded area represents the drier season when streams often run dry. Figure S4 A. are non-riparian permits by catchment area and frequency and B. are permitted peak daily withdrawals across catchment area. (PDF)

AUTHOR INFORMATION

Corresponding Author

*Phone/Fax: 501-450-5919; e-mail: sentrekin@uca.edu.

ORCID

Sally Entrekin: 0000-0002-8276-7832

Notes

The authors declare no competing financial interest.

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