Impacts of hydraulic fracturing on surface and groundwater water resources: A case study from Louisiana, USA.

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Impacts of hydraulic fracturing on surface and groundwater water resources: A case study from Louisiana, USA.

Hanz Unruh¹, Emad Habib¹ and David Borrok²

Abstract

Background: Unconventional oil and gas reservoirs, frequently referred to as shale plays, have been gaining more attention in recent years. Hydraulic fracturing is performed to extract fossil fuels from unconventional reservoirs. Besides possible environmental implications, a better understanding of the potential stress that fracking may cause to water resources at the local or regional scale is still needed. The goal of this study is to assess the impact of current and projected future water demands for fracking on water resources in two main shale plays in Louisiana, USA.

Methods: The analysis is performed in Louisiana's two main shale plays, the Haynesville Shale and the Tuscaloosa Marine Shale, using the Water Supply Stress Index (WaSSI) framework. WaSSI is used to evaluate the stress at a fine watershed scale (HUC12) for annual-average conditions. The study analyzes different scenarios of historical and two future projected fracking conditions that simulate different extraction rates. In each fracking scenario, stresses on both surface and groundwater are evaluated separately. The study is based on a multitude of water supply and withdrawals datasets assembled and disaggregated to the watershed scale.

Results: Under existing conditions, the impact of fracking water demands on surface water resources is within the low stress category in most watersheds in both shale plays. This impact remains low under more aggressive future fracking scenarios. In contrast, groundwater resources appear to be highly vulnerable under both the historical and projected fracking scenarios, especially in the Haynesville Shale where 20 out of the 94 watersheds become medium or highly stressed. If groundwater resources remained as a main source for fracking water, the number of

stressed watersheds increased to 39 and 86 under the two projected future fracking scenarios. The least exploited Tuscaloosa Marine Shale remains mostly under low stress, except in the most aggressive future fracking scenario.

Conclusions: Surface water resources in Louisiana's shale plays seem abundant enough for fracking activities to rely on this source instead of groundwater whenever possible. Groundwater resources in Louisiana are clearly vulnerable to fracking activities, especially for the Haynesville shale play, under current and future projected fracking conditions.

Keywords: Louisiana shale plays, hydraulic fracturing, WaSSI, groundwater stress, surface stress, fracking water demand.

Background

Unconventional oil and gas reservoirs, frequently referred to as *shale plays*, have been gaining more attention in recent years [1], [2]. In order to extract fluids from the relatively impermeable source rock strata, hydraulic fracturing (also known as fracking) of long horizontal well sections is conducted. This fracturing involves the injection of large volumes of water amended with fracking chemicals and proppant (typically sand) into the wells at pressures large enough to fracture the rock and allow gas or oil to flow to the surface [3]. This process has created significant economic value [4], but there are also potential environmental implications. These include the possibility of groundwater contamination and the over-use of local water resources. While many of the water quality implications have been explored (e.g., [5], [6], [7], [8]), a better understanding of the potential stress that fracking may cause to water resources at the local or regional scale is still needed [9]. For example, most previous studies that analyze the costs associated with unconventional fuel production do not address the costs (real or hidden) of accounting for the water

availability required to perform fracking operations (e.g., [10], [11], [12]). Although some studies have related water-stressed regions with fracking activities [6], [13], [14], [15], only a few studies [16], [17], [18], attempted to quantify the potential impact of water used for fracking on the local and regional water resources. A recent national-scale assessment on water use for hydraulic fracturing in the US [20] calls for further studies that examine regional-scale energy and water sustainability challenges.

The importance of quantifying the impact of hydraulic fracturing on water quantity was recently illustrated in the state of Louisiana where concerns over groundwater depletion lead the Louisiana Office of Conservation to issue an order of groundwater emergency in August of 2011 [21], [22] for Southern Caddo County in the Haynesville shale play. In response, the Louisiana Department of Natural Resources established hydraulic regulatory guidelines for Louisiana that encourage the use of surface water for fracking and oil/gas well drilling purposes with the intention of reducing groundwater depletion. In Louisiana, the development of unconventional gas/oil extraction has grown substantially and has the potential to further expand. Most of the unconventional wells in Louisiana are located in the Haynesville shale play (Figure 1). Around 2,832 active wells are spread over seven counties in Louisiana [23], while many other well locations extend into Texas (Figure 1; [24]). Additionally, the Tuscaloosa Marine shale (TMS) has 33 active wells spread throughout eight counties in east-central Louisiana [25], and an additional ~50 wells are located in southern Mississippi (Figure 1). Recent work on the TMS has shown that there remains considerable oil and gas exploration potential [26], and new wells have recently been completed [27]. This study focuses on understanding the impact of current and projected future water demands for fracking on Louisiana's water resources. We use a water stress approach at a watershed spatial scale to quantify the added stress due to fracking activities. We chose the state

of Louisiana for this study because of growing concerns on water availability for fracking and the absence of any quantitative information on the potential impact of fracking on the freshwater water system. A literature analysis revealed that the actual fracking water use in Louisiana is not documented as part of the regular state or national water use reports [28]. Including the fracking water volumes in water budget analysis is crucial to avoid inaccurate assessment of the current and future water stress and to provide reliable information for water allocation and management policies.

Figure 1: Map of Louisiana shale plays including well locations with water use reported by SONRIS during 2011-2016 [24].

Methods

In this study, a water–budget analysis is used to assess the impact on water resources due to hydraulic fracturing performed in Louisiana’s two main shale plays (the Haynesville Shale and the Tuscaloosa Marine Shale). The analysis is conducted using the Water Supply Stress Index (WaSSI) [29] to evaluate the stress status of a watershed over a selected timeframe. Our analysis is conducted over a fine watershed scale defined by Hydrological Unit Code 12 (HUC12) and for annual-average conditions. The HUC-12 resolution is appropriate for this analysis as it provides

fine details for stressed areas that would be masked if greater scales are adopted [30], [31]. The study analyzes different scenarios of current (referred to as maximum historical fracking scenario), and two future projected hydraulic fracturing conditions (possible maximum extraction, and maximum extraction). In each fracking scenario, stresses on both surface water and groundwater are evaluated separately.

Water stress metric:

The Water Supply Stress Index (WaSSI) [29] is expressed as the ratio of water demand (withdrawals) to water supply. A modified version of WaSSI is used to examine the stress for surface water and groundwater separately. Water demands are separated into surface and groundwater based on the information available from United States Geological Survey (USGS) [28] so that the surface and groundwater stress metrics can be assessed separately. Whenever the fracking demand is incorporated into the stress metric, it is assumed that the fracking water demand is coming from one source only, either from surface or groundwater. This assumption is driven by the absence of any specific information on the source of water withdrawals for fracking operations. The WaSSI for surface ($WaSSI_{SWi}$) and groundwater ($WaSSI_{GWi}$) were estimated for a certain watershed (i) using the following two equations:

$$WaSSI_{GWi} = WW_{GWi} / WS_{GWi} \quad (1)$$

$$WaSSI_{SWi} = WW_{SWi} / [(1 - ENV) * WS_{SWi}] + WW_{SWi} \quad (2)$$

where WS is the total water supply, WW is the total water withdrawal, and ENV is an environmental flow requirement. The water stresses are calculated for the watersheds in Louisiana located within the two shale plays, the Haynesville and the Tuscaloosa. The surface water supply (WS_{SW}) for each watershed is calculated as the summation of two components: the equivalent

volume of the annual averaged gauged (streamflow) at the watershed outlet, and the volume of water withdrawn inside each watershed. This second component is added in order to represent the total amount of flow in its natural condition (i.e., before water is removed). The groundwater supply (WS_{GW}) corresponds to the mean-annual natural groundwater recharge. The environmental factor (ENV) is used to ensure provision for environmental requirements in the streams [32], [33]. In this current study, a conservative 50% factor (i.e., $ENV=0.5$) was chosen to ensure fulfilling environmental demands.

Once the surface and groundwater WaSSI are estimated in each watershed, it can be classified into different categories similar to the concept of critical ratio [34], [35]. Following Eldardiry et al. (2016) [19], the following thresholds were used: low stress: $WaSSI < 0.50$, medium stress: $WaSSI$ between $0.50 - 1.00$, and high stress: $WaSSI > 1.00$. The WaSSI assessment will be presented only over the spatial domains of the two shale plays; a Louisiana statewide non-fracking WaSSI assessment is available in an earlier study [19].

Water Supply and Withdrawal Datasets:

The datasets used in this study are summarized in Table 1. Surface and groundwater supplies were acquired from national-scale models and datasets. Both are downscaled and projected into a HUC-12 watershed spatial scale. Surface water supply estimates are obtained from the National Hydrography Dataset (NHDPlus) [36], which reports annual average streamflow. Using streamflow routed through the flow lines network, the mean annual flow estimated for each flow line represents the average over the period from 1971-2000 [37]. Estimates of the annual average recharge rate for groundwater were taken from the USGS in a gridded format with a resolution of 1-kilometer. The USGS dataset represents the mean-annual natural groundwater recharge, which is estimated by multiplying grids of mean annual runoff values from a 1951-1980 [38] by the base-

flow index (BFI) values [39]. In the case of groundwater availability, the recharge rates were averaged across the 1-km² grids within each watershed.

Most historical water withdrawals in Louisiana come from surface water sources and are distributed across four main use categories: agriculture, industrial, power generation, and public supply. A lesser but still important share of the withdrawals in Louisiana originate from groundwater sources, and include two additional categories, livestock and rural domestic. Water withdrawals for fracking purposes are typically quantified under the category of Mining; however, in the state of Louisiana, such information is not currently available [28]. All water withdrawal datasets used in this study, except fracking, were obtained from a public report updated every five years since 1960 by the USGS with the support of the Louisiana Department of Transportation (DOTD) [40]. According to the 2010 USGS report [28], the most recent one available at the time of this analysis, the total surface water withdrawals in Louisiana were 7,000 Million gallons per day (MGD) or 26.50 Million of cubic meters per day (MCMD), and total groundwater withdrawals were about 1,600 MGD (6.06 MCMD). All withdrawals are documented as annual values and presented for each county in the state. In the current study, the 2010 year annual-average water withdrawals dataset is used as a base year for the current and future fracking scenarios. County-scale water withdrawals were disaggregated into a HUC-12 watershed scale using a spatial disaggregation framework developed earlier [19]. The framework is based on a geometric weighting scheme to incorporate spatially-distributed factors (e.g., crop area, surface water locations, etc.) of the water use from within each county level to a watershed scale.

Unlike other water use sectors, fracking water volumes are not reported in the DOTD and USGS annual reports. Instead, fracking water withdrawal data are available through the fracfocus website [23] for every month from year 2011 to 2016 (Figure 1). For example, the numbers of wells in

Louisiana with water demand reported in 2011 reported by Fracfocus.org were 567 wells. The fracking water is reported for each drilled well, and each well is coded by an API number which is a unique numeric identifier assigned by the American Petroleum Institute [41]. A shapefile with the specific locations of the wells, available from the Louisiana Strategic Online Natural Resources Information System (SONRIS) [42], was overlayed with the watershed map to collocate the wells with their respective HUC-12 watersheds. To calculate the annual water use for fracking, the monthly fracking water volumes were added up for all wells inside each watershed. While a well can potentially be fracked 1 to 3 times out of its production life time [23] and the duration of fracking process may last only for few days or weeks [43], we treated the total fracking water use as if it were spread over the entire year since the time scale of the analysis is annual.

Table 1 Source of datasets used in this study.

Source	Variable	Spatial scale	Temporal scale
NHDPlus	Surface water supply	Streamlines	Annual average (1971-2000)
USGS	Groundwater supply	1 x 1 km ²	Annual average (1951-1980)
Fracfocus.org	Oil and gas wells water use	Well	One-time event from 2011-2016
USGS	Surface water withdrawals	County	Annual average (2010)
USGS	Groundwater withdrawals	County	Annual average (2010)

Hydraulic fracturing water demand scenarios:

This study assesses the water stress under current and future scenarios of water demands for hydraulic fracturing. In the stress calculations, 2010-average annual water supply values for both surface and groundwater sources are used and remain fixed for all the scenarios (Table 1). The first scenario, referred to as “Base Case”, considers the 2010 average annual water demands (e.g. municipal, industrial, thermoelectric, public supply, livestock, and rural domestic) without

including the demand of water for fracking. The second scenario, referred to as the “Maximum historical fracking scenario”, includes all water demands plus the calculated fracking water demand for 2011, which represents the year with the maximum number of fracked wells reported in Louisiana historically. A total of 567 wells were reported in 2011, including 554 in the Haynesville and 33 in the Tuscaloosa [23]. These represent 42% of the total 1,364 wells that reported water used for fracking during the period of 2011 to 2016. While only 1,364 wells reported water use for fracking, a total of 2,865 wells has been identified and coded by SONRIS by the end of 2016 for the Haynesville (2,832 wells) and the Tuscaloosa (33 wells). A third hypothetical scenario, referred to as “Maximum possible fracking”, provides an upper boundary of water demand as if all 2,865 existing wells in the shale plays are fracked during a single year. In this scenario, average fracking water demand values are assigned to each well and then incorporated to the stress index calculations. Estimates of water volumes are assigned for each shale play using average water uses from the reported wells. The data available reveals that 8,704.90 MGD (32.95 MCMD) of water for fracking was used by 1,341 wells in Haynesville shale play. For the Tuscaloosa, which is clearly a less developed shale play, only 102.34 MGD (0.39 MCMD) of water for fracking have been used for 33 reported wells. Therefore, the average values of 6.49 (0.025) and 4.45(0.017) MGD (MCMD) /well were used in Haynesville and Tuscaloosa, respectively. In addition to water for fracking, a mean value of 0.32(0.0012) MGD (MCMD)/well was used to account for water use for drilling and cement. This estimate was based on the publication Life Cycle Water Consumption for Shale Gas and Conventional Natural Gas [44]. Note that for all the previously described scenarios (e.g. Base Case, Maximum Historical Fracking, and Maximum Possible Fracking), water stress is assessed only for watersheds with already existing fractured wells. Finally, a fourth hypothetical fracking scenario, “Maximum Extraction”,

is considered based on estimations of how many wells would be required in order to maximize recovery in each shale play. This scenario resembles an extreme upper boundary in terms of water consumption. Results from this hypothetical scenario can provide stakeholders (e.g., water managers, authorities of oil and gas companies) with an idea of which watersheds or regions within these plays could have water sustainability issues in an oil boom. Based on the Louisiana Department of Natural Resources (2011) report [45], a total of 10,000 wells are likely required to maximize fuel extraction in the Haynesville in Louisiana. So far, only the 28% (2,832) of these wells actually exist. Currently, there is no published information on the potential number of wells required to reach maximum recovery of the hydrocarbons stored in the Tuscaloosa Marine shale reservoir. Several studies indicate that a potential of 7 billion barrels of oil are stored in Tuscaloosa [46], [47]; however, for the current study, a conservative estimated ultimate recovery (EUR) of 700 million oil barrels (BBL) is considered according to the report “Tight Oil: A primer” (2014) [47] by the Louisiana Department of Natural Resources Technology Assessment Division. To estimate the number of wells required for the maximum oil extraction of the whole shale play, the production per well was estimated based on the 19 wells that reported production values (oil barrels) in Tuscaloosa. The production of these wells was averaged over a period of 36 months and then plotted as a function of month of operation (Figure 2). The 36-month period was selected based on the economic feasibility of the well [48]. The pattern observed for oil production in Tuscaloosa wells is consistent with the literature for other US regions [49]. For Tuscaloosa’s 19 active wells, the recorded average monthly oil production per well was 110,913 oil barrels in a period of 36 months of operation. Based on this information, the numbers of wells required to fully exploit the oil available in the Tuscaloosa shale play is estimated as follows: 700 Million BBL /

110,913 BBL per well, which results in a total of 6,311 wells. This estimation assumes water consumption where each well will be fracked once in its lifetime.

Figure 2: Average oil production per well in Tuscaloosa Marine shale play during the first 36 months.

The spatial distribution of wells in the maximum extraction scenario was based on locating future wells in watersheds that do not contain any wells but are inside the boundaries of the shale play (Figure 1). While new wells could be drilled in HUCs with existing wells, this assumption is reasonable given the lack of information on placing of future wells that would inform a more specific approach for well distribution. In the Haynesville, there are 73 watersheds that do not contain any wells. Therefore, the additional 7,168 (10,000 total minus 2,832 existing wells) were equally distributed over the 73 well-free watersheds units resulting in 98 new wells per watershed. The same average water demand for fracking estimated previously is assigned to each new well. Similarly, the additional (6,312–33=6,279) wells in Tuscaloosa were equally distributed along the 311 well-free watersheds, resulting in 20 wells per watershed in order to simulate a maximum extraction scenario. Table 2 summarizes the number of wells and watersheds units involved per hydraulic fracturing scenario. These new fracking water demand estimates were incorporated into the surface and groundwater WaSSI based on equations (1) and (2), assuming that fracking water is fully taken from one source only, either from surface or groundwater. The assumption of using

all groundwater or all surface water is probably not realistic, but it is necessary given the fact that we cannot predict the relative distributions from these two sources. Moreover, by examining the end member scenarios of assigning 100% of fracking water volumes into surface or groundwater sources, we can examine the upper ends of the WaSSI stress for each source.

Table 2: Number of wells and watersheds addressed per scenario.

Scenario	Number of wells		Number of watersheds	
	Haynesville	Tuscaloosa	Haynesville	Tuscaloosa
Base Case	0	0	94	19
Maximum historical fracking	554	13	94	19
Possible maximum extraction	2,832	33	94	19
Maximum extraction	10,000	6,312	167	330

Results and Discussion

Base Case vs. Maximum historical fracking scenario:

For the Base Case scenario, where surface and groundwater stresses are assessed without including the fracking water use, the results (*Figure 3*, Table 3 and Table 4) show fairly low WaSSI stress values for surface water in all the watersheds of both shale plays. As noted earlier, and due to the absence of more specific information on the source of fracking water, the stress calculations assigned the entire fracking water use to either surface or groundwater. Except for one watershed, surface water stress fell into the low stress category ($\text{WaSSI} < 0.5$). For groundwater, the stress results are noticeably different (*Figure 4**Figure 3*). Although most of the watersheds are still under low stress, 12 out of the 94 watersheds (13%) in the Haynesville shale play have stresses greater than 0.50, and five (5%) are highly stressed. This indicates that groundwater resources are expected to be more vulnerable to the addition of groundwater demand for fracking purposes in the

Haynesville shale play area. For the Tuscaloosa play groundwater stresses are mostly lower than 0.50, with only one unit out of the 19 watersheds having a stress ratio over 1.

By examining the maximum historical fracking scenario, and when the fracking water use was assumed to be fulfilled entirely from surface water resources, the results show that there is no significant change in the surface water stresses for most watersheds (*Figure 3*). However, in the case of assigning the fracking water demand to groundwater resources, the maximum historical fracking scenario shows that more watersheds are affected due to fracking operations (*Figure 4*). In the Haynesville, seven watersheds are showing groundwater stress values over one, and 13 watersheds are now under medium stress (*Table 3*). The assumption of fulfilling the fracking water demand from groundwater resources almost doubled the number of watersheds in the medium stress classification. On the other hand, the Tuscaloosa's watersheds were not affected measurably by fracking water demand, which is expected since only 19 wells are accounted for in this part of the study (*Table 4*).

Figure 3: Results of surface water WaSSI for the base case (left) and maximum historical fracking scenario (right). WaSSI values for watersheds outside the domains of the shale plays are not displayed.

Figure 4: Same as Figure 4 but for groundwater WaSSI.

Possible maximum extraction scenario

The results of the possible maximum extraction scenario are illustrated in Figure 5, Figure 6, Table 3, and Table 4. Surface water stress results showed no significant increase in either of the shale plays, except for one watershed in Haynesville (Figure 5). While more watersheds, especially in the Haynesville, display higher stress levels, their surface WaSSI values remain below 0.1. Nonetheless, if all the fracking water demand was attributed to groundwater use, then groundwater resources will be affected significantly (Figure 6), as 23 of the watersheds become highly stressed, and another 16 become medially stressed over the Haynesville shale play. In the Tuscaloosa, only one watershed is classified with high stress and the remaining 18 are still in the lower stress category.

Figure 5: Results of surface water WaSSI for the base case (left) and possible maximum extraction scenario (right). WaSSI values for watersheds outside the domains of the shale plays are not displayed.

Figure 6: Same as (Figure 5) but for groundwater WaSSI.

Maximum extraction scenario

This extreme scenario simulates a maximum extraction of the oil/gas stored in both shale plays over a brief time period (one year). This increase in the number of wells means a significant increase in the fracking water demand. Despite this sudden increase in the number of wells per watershed compared to other scenarios (Table 2), surface stress values remain mostly below 0.50 in both shale plays (Figure 7). As noted earlier, stress under the Base Case scenario was assessed only for watersheds that already have fractured wells. In order to compare the results with and without fracking, the surface and groundwater stress calculations in the Base Case scenario were expanded geographically across the newly added watersheds in Haynesville and Tuscaloosa

domains (Figures 3 and 4). When water use for fracking was assumed to come from groundwater, the watersheds showed much higher levels of stress (Figure 8). In this case 53 of the Haynesville watersheds become highly stressed, and 35 were at a medium stress level (Table 3 and Table 4). In the Tuscaloosa over 43 watersheds showed high groundwater stress values and 27 showed medium stress values.

Figure 7: Results of surface water WaSSI for the base case (left) and maximum extraction scenario (right). WaSSI values for watersheds outside the domains of the shale plays are not displayed.

Figure 8: Same as Figure 7 but for groundwater WaSSI

Table 3: Haynesville stressed watersheds per scenario and water resource.

WaSSI Stress metric	Number of Haynesville watersheds (and percentages) per scenario and source							
	Base case		Maximum historical fracking		Possible maximum extraction		Maximum extraction	
	SW	GW	SW	GW	SW	GW	SW	GW
High > 1	1(1)	5(5)	1(1)	7(7)	1(1)	23(24)	2(0)	53(32)
Medium 0.50-1.00	0(0)	7(7)	0(0)	13(14)	0(0)	16(17)	0(0)	35(21)
Low < 0.50	93(99)	82(88)	93(99)	74(79)	93(99)	55(59)	165(100)	79(47)

Table 4: Tuscaloosa Marine Shale stressed watersheds per scenario and water resource.

WaSSI Stress Metric	Number of Tuscaloosa watersheds (and percentages) per scenario and source							
	Base case		Maximum historical fracking		Possible maximum extraction		Maximum extraction	
	SW	GW	SW	GW	SW	GW	SW	GW
High > 1	0(0)	1(5)	0(0)	1(5)	0(0)	1(5)	2(0)	43(13)
Medium 0.50-1.00	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	1(0)	27(8)
Low < 0.50	19(100)	18(95)	19(100)	18(95)	19(100)	18(95)	327(100)	260(79)

A summary comparison between each of the three different scenarios and the Base Case is presented in Table 5. This table reports the number of watersheds that shifted their stress levels by at least one level (i.e., from low to medium, medium to high, or low to high) compared to their without-fracking condition. A significant increase in the groundwater stress level is observed in the Haynesville shale play where more watersheds are involved in hydraulic fracturing activities. For the maximum historical fracking scenario, 10 watersheds shifted from a lower to a higher stress level. The “possible maximum extraction” and “maximum extraction” scenarios further increased the number of watersheds migrating to higher levels of stress to 45 and 107 watersheds, respectively (Table 5). For the Tuscaloosa play, the groundwater stress levels are not significant

for maximum historical fracking and possible maximum extraction scenarios considering that only 19 watersheds units contain one well or more. However, for the maximum extraction scenario, the shift from low to medium or high groundwater stress is more evident (Table 5). Maximum extraction scenario expands the area of influence of fracking activity inside the shale play area, simply due to the assumption that this scenario incorporates new wells into watershed that did not contain any wells in the other scenarios.

Table 5: Number (and percentage) of watersheds that shifted their stress levels by at least one level (i.e, from low to medium, medium to high, or low to high) compared to their without-fracking condition in both shale plays.

Shale play	Scenario		
	Maximum historical fracking	Possible maximum	Maximum extraction
Haynesville	10 (11%)	45 (48%)	107 (64%)
Tuscaloosa	0 (0%)	0 (0%)	112 (34%)

Conclusions and Future Work

Hydraulic fracturing activity requires large volumes of water as a primary operational component. This can have negative implications for the sustainability of freshwater resources. In this study, the WaSSI stress analysis framework was implemented to assess the impact on current and future water resources due to hydraulic fracturing in Louisiana's two main shale plays, Haynesville and Tuscaloosa. Three fracking scenarios were simulated within the WaSSI framework to evaluate recent conditions (maximum historical fracking scenario) and two future projections that represent moderate and aggressive fracking activities. The stress analysis was performed for surface water and groundwater components separately to determine which resource is more vulnerable. Based on the results of the three scenarios, the following two main conclusions can be made (1) The surface water in the watersheds located with Louisiana's shale plays seems to be sufficient to meet

water demands for hydraulic fracturing activities performed in the oil and gas extraction processes. Therefore, fracking activities should rely on this source of water instead of groundwater whenever possible, and (2) Groundwater resources in Louisiana are clearly vulnerable to hydraulic fracturing activities. Current water uses for hydraulic fracturing resulted in significant stresses on the groundwater system, especially for the Haynesville shale play. The analysis showed that such stresses are expected to increase significantly and expand spatially under future projected hydraulic fracturing activities.

Future work

State oil and gas companies will need to weigh economics of production and water sustainability in an oil boom. While the results of this study suggest that surface water resources can be adequate to sustain the current and future demands of water for hydraulic fracturing activities in Louisiana, economic factors should be taken into considerations. These include costs for developing surface water storage facilities, especially in areas with little topographic relief such as Louisiana and other coastal states, as well as costs associated with transportation of surface water to extraction sites. Furthermore, the feasibility of other alternative resources that are not suitable for public or irrigation uses (e.g., brackish groundwater), and the potential use of recycled flowback and produced water should be assessed as viable strategies that can alleviate the impact of hydraulic fracturing on the sustainability of freshwater systems.

Abbreviations

BBL: Oil barrel; BFI: Base-flow index; MCMD: Million of Cubic meters per day; DOTD: Louisiana Department of Transportation; ENV: Environmental Flow Requirement; EUR: Estimated ultimate recovery; HUC12: Hydrological Unit Code 12; MGD: Million of Gallons per day; NHDPlus: National Hydrography Dataset; SONRIS: Strategic Online Natural Resources

Information System; TMS: Tuscaloosa Marine Shale; USGS: United States Geological Survey; WaSSI: Water Supply Stress Index; $WaSSI_{GW_i}$: Water Supply Stress Index for groundwater at a certain watershed (i); $WaSSI_{SW_i}$: Water Supply Stress Index for surface water at a certain watershed (i); WS: Total water supply; WS_{GW} : Groundwater supply; WS_{SW} : Surface water supply; WW: Total water withdrawal.

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Authors' contributions

The three authors contributed collectively to this research work. HU collected the datasets, developed codes and performed the analysis for the fracking scenarios, participated in writing the manuscript. EH and DB participated in writing the manuscript, analyzed and the results, revised

and edited the content, and supervised the research work. All authors read, revised and approved the final manuscript.

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Availability of data and materials

The datasets used during the current study are available from the corresponding author on request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1

Map of Louisiana shale plays including well locations with water use reported by SONRIS during 2011-2016 [24].

Figure 2

Average oil production per well in Tuscaloosa Marine shale play during the first 36 months.

Figure 3

Results of surface water WaSSI for the base case (left) and maximum historical fracking scenario (right). WaSSI values for watersheds outside the domains of the shale plays are not displayed.

Figure 4

Same as Figure 4 but for groundwater WaSSI.

Figure 5

Results of surface water WaSSI for the base case (left) and possible maximum extraction scenario (right). WaSSI values for watersheds outside the domains of the shale plays are not displayed.

Figure 6

Same as (Figure 5) but for groundwater WaSSI.

Figure 7

Results of surface water WaSSI for the base case (left) and maximum extraction scenario (right). WaSSI values for watersheds outside the domains of the shale plays are not displayed.

Figure 8

Same as Figure 7 but for groundwater WaSSI