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Research papers

Baseflow recession analysis in a large shale play: Climate variability and anthropogenic alterations mask effects of hydraulic fracturing

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ABSTRACT

Water resources development and landscape alteration exert marked impacts on water-cycle dynamics, including areas subjected to hydraulic fracturing (HF) for exploitation of unconventional oil and gas resources found in shale or tight sandstones. Here we apply a conceptual framework for linking baseflow analysis to changes in water demands from different sectors (e.g. oil/gas extraction, irrigation, and municipal consumption) and climatic variability in the semiarid Eagle Ford play in Texas, USA. We hypothesize that, in water-limited regions, baseflow (Q_b) changes are partly due (along with climate variability) to groundwater abstraction. For a more realistic assessment, the analysis was conducted in two different sets of unregulated catchments, located outside and inside the Eagle Ford play. Three periods were considered in the analysis related to HF activities: pre-development (1980–2000), moderate (2001–2008) and intensive (2009–2015) periods. Results indicate that in the Eagle Ford play region, temporal changes in baseflow cannot be directly related to the increase in hydraulic fracturing. Instead, substantial baseflow declines during the intensive period of hydraulic fracturing represent the aggregated effects from the combination of: (1) a historical exceptional drought during 2011–2012; (2) increased groundwater-based irrigation; and (3) an intensive hydraulic fracturing activity.

1. Introduction

Groundwater contributes to streamflow, which is crucial for water supply and riverine ecosystem health, and groundwater is also critical for energy generation, especially in water-limited catchments (Mwakalila et al., 2002) where more than a third of the world's population live. Baseflow represents the cumulative outflow of all upstream riparian aquifers (Aksoy and Wittenberg, 2011) and depends on water availability (precipitation and actual evapotranspiration), vegetation (land use and functional CO_2-driven changes (Trancoso et al., 2017)), geology, aquifer properties, and water table depth (Beck et al., 2013; Smakhtin, 2001). Changes in groundwater storage and their subsequent effects on baseflow and play an important role in the hydrologic cycle (He et al., 2016), where anthropogenic impacts, such as aquifer abstraction, can alter the hydraulic gradient and thus, natural discharge to surface water (Smakhtin, 2001; Wittenberg, 2003). Changes in baseflow patterns can be evaluated by means of the relationship between groundwater and surface water during low flow periods through hydrograph analysis (Famiglietti and Rodell, 2013; Hall, 1968; Tallaksen, 1995). A summary of previous research on baseflow changes due to human activities is shown in Table 1.

Additional water demands on aquifers and rivers from unconventional oil and gas resource production could represent a challenge for water security, due to increasing water scarcity and uncertainty related to water supplies for people, energy, food, and ecosystems (Carter, 2015). The complex interaction of the water-energy system has been recognized as a driving force of global change in a variety of ways (Scott et al., 2011), and as a key factor in ensuring sustainability and efficiency in modern economies (Hussey and Pittock, 2012; Stillwell et al. 2011).

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Table 1
Summary of relevant research in baseflow alterations due to climate variability and anthropogenic influence (scientific works related to hydrochemical alterations in the baseflow component were not included). While key findings are numbered (1) to (3) they do not directly relate to the objectives of this study.

Study	Dataset; Methods	Location	Key findings
Sánchez-Murillo et al. (2014)	Daily discharge and precipitation records ranged from 7-74 years (mean = 33 years); Low frequency analysis; baseflow indices; recession methods	26 watersheds across the Pacific Northwest, USA	(1) Baseflow in flat landscapes and in dry warm climates decrease rapidly during summer months; (2) Mean slope basin and the aridity index were found to be the best estimators of baseflow coefficients; (3) Under a combination of several factors (e.g. flatter slopes, low precipitation, high ET rates) some watersheds could experience faster recession times and <1 mm of minimum annual storage
Sawaske and Freyberg (2014)	Streamflow gauged stations ranging from 40 to 80 years (mean = 63.6 years); Annual baseflow recession method (linear model) and recession slope curve method (non-linear model)	54 watersheds in the states of California, Oregon and Washington (gauged stations primarily located in the coastal mountain ranges)	(1) Two different baseflow recession analysis techniques were capable to simulate dry-season flow conditions in a wide range of catchments; (2) Over the past 40–80 years, widespread trends of increasing rates of baseflow recession and decreasing low flow conditions were detected; (3) Northern California and Oregon are especially impacted regions, with more than 60% of the studied watersheds exhibiting decreasing trends in late summer
Hamel et al. (2013)	A review paper on the impacts of urbanization on baseflow patterns	N/A	(1) A state-of-knowledge review on baseflow alterations by urbanization and the potential of source-control stormwater management strategies to mitigate such variations; (2) Several parameters influence baseflow behavior in urban catchments, such as natural features (geology, topography, pre-development vegetation) and anthropogenic factors (urban impervious patches, external return flows); (3) The multiplicity of baseflow metrics and analytical uncertainties, have potentially confusing effects on the interpretation of observed data on baseflow responses to urbanization (further discussion can be found in Hamel et al. (2015))
Thomas et al. (2013)	Daily streamflow records ranged for 1990–2009; A model was proposed to characterize the behavior of coupled groundwater-surface water systems, based on the baseflow recession constant	15 watersheds in New Jersey (USA) with high population density areas	(1) The baseflow recession constant is useful to assess groundwater-surface water interactions; (2) When groundwater withdrawals are ignored, aquifer-streamflow analysis can be biased; (3) The need to incorporate aquifer abstraction to properly characterize baseflow recessions
Wang and Cai (2010a)	A few gauge stations analysed (over a 20 and 30-year period); Low flow magnitude, slope and master recession curves analysis. Human/climate impact diagnosis using the Wang and Cai (2009) approach	Four watersheds in the American Midwest (two urban and two agricultural)	(1) Long-term baseflow slope trends in all watersheds, are induced by human impacts; (2) In urban catchments, decreasing trend of the recession slope in winter and summer is caused by effluent discharges, groundwater abstraction and water diversions; (3) In a watershed with rainfed crops, the decreasing recession slopes is caused by effluent discharge from the towns with no slope change in summer. The watershed with irrigation shows the opposite trend during winter and summer, attributed to seasonal water use regimes and water withdrawal
Wang and Cai (2009)	Streamflow observation for 1946–2006; a proposed model to incorporate groundwater pumping and return flow as variables in the recession process	The Salt Creek urban watershed (Chicago, USA)	(1) This work presents an empirical method to improve baseflow recession analysis, taking into account groundwater pumping and return flow in urban watersheds
Jacques et al. (2009)	Streamflow records (≥30 years) from 23 stream gauges; Long-term trends in winter baseflow assessed using the Kendall-τ test, Theil-lines and least-squares regression for missing data	Watersheds in the Canada's Northwestern Territories, located in permafrost regions	(1) Overall significant upward trends in winter baseflow (0.5–271.6%/yr) and significant increasing mean annual flow; (2) The observed trends can be attributed to climate warming due to permafrost thawing that enhances infiltration and deeper subsurface flowpaths

(continued on next page)

Table 1 (*continued*)

Study	Dataset; Methods	Location	Key findings
Zhang and Schilling (2006)	Streamflow and baseflow analysis for 1940–2003 and a high resolution land use dataset (1950, 1970 and 1992); Water balance and land use change analysis	Mississippi River basin (USA)	(1) A trend of increasing streamflow in the Mississippi River basin since 1940s, attributed to an increase in baseflow, instead of precipitation; (2) Long-term baseflow increase as a result of land use change over the last 60 years during expansion of soybean; (3) Conversion of perennial vegetation to seasonal crops decreased ET and surface runoff and increased groundwater recharge, baseflow and streamflow
Kienzle (2006)	Streamflow measurements from 1967–2004; Runoff analysis, recession index and master recession curve	Upper Battle River basin (Alberta, Canada)	(1) This work presents a procedure that enables the estimation of natural baseflow in gauged watersheds; (2) The recession index can be an indicator for streamflow recovery; (3) Baseflow is extremely low after a multi-year drought (2001–2003)
Wittenberg (2003)	Daily streamflow data of rivers in different climate zones	Watersheds in Germany, Western Australia, Turkey	(1) Shallow, unconfined aquifers respond as non-linear reservoirs, instead of the traditional exponential function of a linear reservoir; (2) Recession properties are subject to seasonal changes due to ET and groundwater abstraction; (3) Baseflow separation and recession analysis are useful for quantifying seasonal and man-made influences in river-aquifer interactions
This study	Daily streamflow records from 1986-2015. Three periods analysed related to HF activities: 1980–2000, 2011–2008, 2009–2015; Baseflow recession analysis and hydrograph separation method	32 watersheds in the Eagle Ford shale gas/oil play (Texas, USA) located inside (11) and outside (21) the play	(1) A conceptual framework was tested to quantitatively assess the HF activities on baseflow behavior in semi-arid regions; (2) Baseflow changes were detected. However, cannot be directly associated to a specific water use, such as HF; (3) Instead, a clear aggregated effect from the combination of a historical drought of 2011 (mainly), regional groundwater abstraction for irrigation purposes, and intense HF activity (2009–2015) have caused baseflow decline in catchments located inside and outside the play

Unconventional oil and gas development could become a global issue with important environmental consequences, since the paradigm shift in oil and gas production. The U.S. Energy Information Administration (EIA) reported technically recoverable resources in shale rocks in order of ~206 trillion m^3 of gas and 345 billion barrels of oil, within 137 plays and 41 countries, with ~40% in arid/semiarid regions with high water stress (EIA, 2013). Unconventional oil and gas development involves a combination of vertical/horizontal drilling and hydraulic fracturing (HF), within a low permeability reservoir, through high pressure injection of water (Gallegos et al., 2015).

In contrast, a number of studies highlight that some of the impacts of unconventional oil and gas development on water resources are not exclusive to the oil and gas industry (Bordeleau et al., 2015; Hamilton et al., 2015). For instance, Scanlon et al. (2014b) and Zhang and Yang (2015) discussed that, in terms of water intensity, shale gas development is not necessarily high-water consuming, when compared to conventional hydrocarbon production and other energy producing industries. Chen and Carter (2016) reported ~ 930 Mm^3 of cumulative water use from 2008 to 2012 to hydraulically fracture ~80,000 wells in 14 states of the U.S. However, it should be noted that the amount of water required for hydraulic fracturing (HF), is highly variable and depends on the physical and geological attributes of the hydrocarbon reservoir, well depth, vertical versus horizontal wells, length of horizontal wells, number of HF stages, operator, and others (Nicot and Scanlon, 2012). As a result, reported water uses for HF per well in each play vary from 13,000 m^3 in the Niobrara shale play in Colorado in 2012 (Vengosh et al., 2014) to 20,000 m^3 in the Marcellus play in 2010 (Jiang et al., 2011). Despite the magnitude of these volumes, water use for HF has been reported to be on the order of 1–4% of statewide water withdrawals in Texas, North Dakota, and Oklahoma (Murray, 2013; Nicot and Scanlon, 2012).

Water impacts of HF have been reported at the local scale with regards to declining groundwater levels (Arthur et al., 2009) or changes in aquifer water budgets (Bené et al., 2007). Barth-Naftilan et al. (2015) reported about the influence of HF on streamflow of 300 rivers within Susquehanna River Basin in Pennsylvania (which includes the area of the Marcellus Shale Play) and concluded that streams with small drainage areas (<130 km^2) were more affected. However, HF impacts on baseflow (arguably the contribution of groundwater to catchment discharge during dry periods) remains unclear.

The aim of this study is to investigate the baseflow patterns in the largest shale oil producer globally (Scanlon et al., 2014a) over the last thirty years. The specific objectives are to: (i) analyze spatial and temporal changes of baseflow recession parameters; (ii) infer impacts of hydraulic fracturing on catchment discharge; and (iii) assess the influence of climate variability (the 2011 drought) on baseflow decline. This analysis is timely as previous impact studies of unconventional oil and gas development on water resources have not generated a scientific framework aimed at understanding the potential consequences of large-scale shale gas production on low flows hydrology.

2. Study site and materials

2.1. Study area and data

The study area consisted of the Eagle Ford play in south Texas (Fig. 1), which is one of the largest oil and gas producing regions in the USA. In this region, shale gas and oil production began in 2008–2009 and increased more rapidly than in other plays, accompanied by a rise in groundwater consumption for HF purposes (Kuwayama et al., 2015; Nicot and Scanlon, 2012; Scanlon et al., 2014a). The Eagle Ford play is located in an arid/semiarid region where the main water source for HF withdrawals is the Carrizo-Wilcox aquifer, a major water source for irrigation and municipal consumption. Past droughts and high rates of groundwater withdrawal for irrigation during the last century have resulted in large declines in groundwater levels in some parts of the play, including in the unconfined sections generating baseflow (Deeds et al., 2003; Scanlon et al., 2014a).

The climate of the region ranges from semiarid in the southwest to more humid towards the northeast, with mean precipitation ranging from 500 mm/year to 1100 mm/year (1983–2016, Livneh et al., 2015). Seasonal precipitation regimes are relatively uniform with monthly peaks during May-June and August-September. Catchments located close to the coast are more prone to experience intense storms during the hurricane season (June-October).

This research uses publicly available data from thirty-two catchments whose stream gauging stations were located inside (eleven stream gauges) and outside (twenty-one stream gauges) the Eagle Ford shale footprint (Fig. 1). Each stream gauging station had daily streamflow measurements at least from 1986 to 2015 (http://waterdata.usgs.gov/nwis) and were not regulated by any upstream dam or reservoir (see Table 2). The gauging stations are located in relatively flat terrain with mean catchment elevations ranging between 22 and 502 m (above sea level, masl) and mild mean catchment slopes ranging from 1 to 12%. The drainage area of the selected catchments selected varies from 32 km^2 to 39,972 km^2, with most of the catchments area less than 2000 km^2. Because of the precipitation regime within the study region, it is difficult to characterize a low flow season given the existence of two high-flow peaks throughout the year (typically May-June and October-November); nevertheless, streamflow intermittency typically occurs in two thirds of the analysed catchments (11 inside and 21 outside the Eagle Ford shale footprint). Indicators of groundwater contribution to rivers were calculated through baseflow separation, baseflow recession analysis, storage-discharge relationships, and flow duration-curves. Here, baseflow consists of low discharge rates (a few tens of liters per second) in most of the streams. In addition, three periods were defined in terms of the play production: (1) pre-development HF period (1986–2000); (2) moderate HF period (2001–2008); and (3) intensive HF period (2009–2015).

Precipitation anomalies (1986–2013) were estimated using a high-resolution hydrometeorological data set developed for North America (Livneh et al., 2015). In addition, temporal deficits in hydrological storage were inferred with the support of terrestrial water storage anomalies retrieved by the Gravity Recovery and Climate Experiment mission (GRACE) satellites for 2003–2015 (Landerer and Swenson, 2012). Groundwater use for municipal and irrigation consumption was obtained from the Texas Water Development Board (TWDB) database TWDB for 1986–2015. Finally, the location of HF wells in the play was obtained from the FracFocus database (https://fracfocus.org/) for the period 2011–2014.

2.2. Baseflow recession analysis

Daily time series of streamflow were analysed throughout the year, and a hydrograph separation filter algorithm (Lyne and Hollick, 1979) was applied to derive time series of baseflow (Qb) from total flow (Q), thereby mean annual baseflow volume

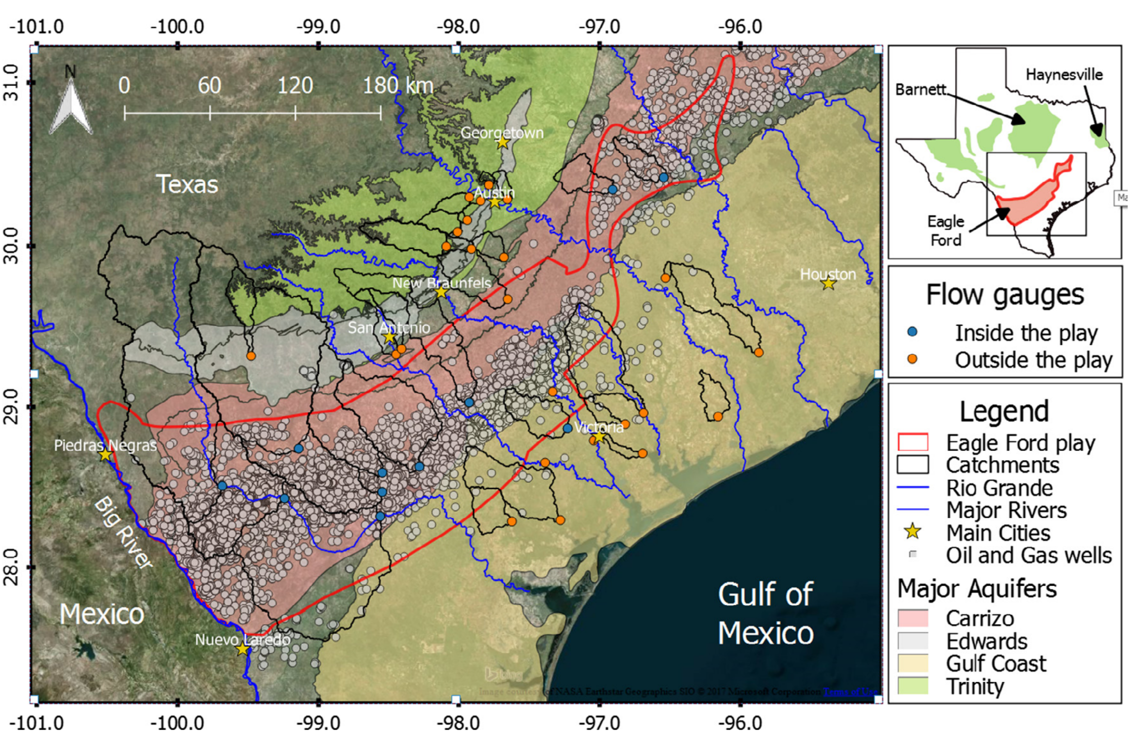

Fig. 1. Location of the streamflow gauges inside (blue dots) and outside (orange dots) the Eagle Ford Shale play (red polygon). The gray points represent the location of horizontal wells for hydraulic fracturing obtained from the FracFocus database (for 2011–2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Location of streamflow gauges and main properties of the analysed catchments. Main aquifer is the main groundwater source for each catchment as a function of its proportional area; Location is given in the NAD83 coordinate reference system; Area is the drainage area of the catchment in km2; Perim is the perimeter of the catchment given in km; Zmean, Zmin, Zmax are the mean, minimum and maximum catchment elevation, respectively; # wells are the number of wells inside the catchment area, obtained from the FracFocus database for 2011–2014.

	Code	Predominant aquifer	Location		Catchment properties					No. wells
			Longitude	Latitude	Area	Perim	Zmean	Zmin	Zmax	for hydraulic fracturing
Inside the Eagle Ford play	8109700	Carrizo-Wilcox	96 °54′21.99″W	30 °20′35.7″N	607	189	147	99	226	4
	8110100	Carrizo-Wilcox	96 °32′35.97″W	30 °25′2.42″N	498	176	121	75	199	44
	8176900	Gulf of Coast	97 °13′32.45″W	28 °51′45.92″N	926	234	91	41	180	395
	8186000	Carrizo-Wilcox	97 °55′29.7″W	29 °1′26.46″N	2121	573	252	91	617	73
	8193000	Carrizo-Wilcox	99 °41′5.06″W	28 °30′14.38″N	10408	921	384	153	740	476
	8194000	Carrizo-Wilcox	99 °14′32.62″W	28 °25′32.96″N	13383	1084	338	118	740	3116
	8194500	Carrizo-Wilcox	98 °33′44.68″W	28 °18′49.04″N	20976	1470	268	64	740	4195
	8205500	Carrizo-Wilcox	99 °8′31.45″W	28 °44′12.75″N	8924	664	347	144	739	260
	8206600	Carrizo-Wilcox	98 °32′54.67″W	28 °28′0.09″N	11377	904	302	77	739	1797
	8206700	Carrizo-Wilcox	98 °32′52.82″W	28 °35′15.98″N	2042	395	175	85	318	348
	8208000	Carrizo-Wilcox	98 °16′43.35″W	28 °37′26.77″N	2971	400	138	62	256	560
Outside the play	8117500	Gulf of Coast	95 °52′3.93″W	29 °20′1.18″N	1220	362	59	24	142	–
	8154700	Trinity	97 °47′7″W	30 °22′20.42″N	58	51	271	177	341	–
	8155200	Trinity	97 °55′26.02″W	30 °17′49.29″N	230	105	341	235	460	–
	8155240	Trinity	97 °50′38.64″W	30 °16′28.12″N	277	129	328	192	460	–
	8158600	Trinity	97 °39′14.79″W	30 °17′0.94″N	141	88	218	142	302	–
	8158700	Trinity	98 °0′28.54″W	30 °5′1.36″N	320	121	377	278	512	–
	8158810	Trinity	97 °56′20.08″W	30 °9′20.87″N	32	30	326	270	380	–
	8160800	Gulf of Coast	96 °31′50.95″W	29 °47′58.61″N	44	45	110	77	141	–
	8162600	Gulf of Coast	96 °9′27.09″W	28 °56′11.68″N	409	164	23	14	43	–
	8164000	Gulf of Coast	96 °41′12.72″W	28 °57′33.17″N	2074	393	82	21	180	–
	8164600	Gulf of Coast	96 °49′1.42″W	28 °53′22.39″N	210	141	47	24	79	–
	8164800	Gulf of Coast	96 °41′35.9″W	28 °42′28.45″N	151	138	22	4	40	–
	8171000	Trinity	98 °5′16″W	29 °59′37.31″N	919	230	423	257	619	–
	8171300	Trinity	97 °54′33.87″W	29 °58′41.82″N	1080	275	403	199	619	–
	8172000	Carrizo-Wilcox	97 °39′6.12″W	29 °39′51.5″N	2172	437	299	110	619	–
	8172400	Trinity	97 °40′43.16″W	29 °55′37.1″N	287	107	192	139	275	–
	8178565	Trinity-Edwards	98 °27′1.17″W	29 °19′20.82″N	422	196	269	158	547	–
	8178800	Trinity-Edwards	98 °24′39.28″W	29 °21′23.94″N	485	185	294	173	452	–
	8189500	Gulf of Coast	97 °16′39.38″W	28 °17′27.46″N	1804	359	73	14	167	–
	8189700	Gulf of Coast	97 °37′18.67″W	28 °16′56.54″N	639	177	77	35	138	–
	8198500	Trinity-Edwards	99 °28′47.09″W	29 °18′48.05″N	618	234	502	279	716	–

($Vb = \sum Qb$, area under the baseflow hydrograph), and the baseflow index ($BFI = \sum Qb/\sum Q = Vb/Vt$, contribution of baseflow to total streamflow) were computed.

Then, baseflow recession analysis was performed using a non-linear storage-discharge relationship that describes the hydrograph's recession limb proposed by Brutsaert and Nieber (1977):

$$\frac{dQ}{dt} = -aQ^b \tag{1}$$

In this work, following the separation of baseflow from the original hydrograph, Q the total discharge is replaced by Q_b so that the estimation of parameters *a* and *b* (and their changes during the HF development periods) mostly represent groundwater discharge to streams.

From the double integration of Eq. (1), groundwater storage contributing to baseflow (S) is derived as follows (Wang and Cai, 2010b):

$$S = \frac{1}{a(2-b)} Q_b^{2-b} \tag{2}$$

Eq. (2) represents a storage-discharge relationship, where the recession parameter *a* is inversely proportional to S, so that as *a* increases, S decreases and, vice versa.

2.3. Impacts of water use on stream baseflow

The recession analysis was then grouped into three periods: (1) pre-development (1986–2000); (2) moderate hydraulic fracturing (2001–2008); and (3) intensive hydraulic fracturing (2009–2015). The pre-development HF period was defined by the available time series before any relevant activity related to the development and exploitation of unconventional hydrocarbons. The moderate hydraulic fracturing period was defined as the first eight years in which hydraulic fracturing operations had not reached their full potential (Nicot and Scanlon, 2012). The intensive hydraulic fracturing period was defined as the time since the beginning of substantial water withdrawal from groundwater sources and its subsequent injection in deep shale formations (Scanlon et al., 2014b). Moreover, to identify whether there is any correlation between water withdrawals for HF usage and baseflow decline, we used spatial information related to number of oil/gas wells in each watershed (Fig. 1).

A preliminary baseflow recession analysis showed that parameter *b* for each catchment did not differ significantly among the three periods. We then assumed that: (1) the storage-discharge relationship is temporally invariant, i.e., intrinsic to the watershed (Wittenberg, 1999); and (2) any changes detected in the baseflow recession parameter *a* will depend on active catchment storage, which could be associated with an increase in groundwater abstraction due to intense HF activity. The statistical significance of the results were obtained using a linear regression t-test and a Mann-Kendall non-parametric test. Such tests were applied to test for annual changes in the baseflow index and baseflow volumes from the pre-development period to the moderate hydraulic fracturing period, and from the moderate hydraulic fracturing to the intensive hydraulic fracturing period. Changes were defined to be significant for $p < 0.05$. Moreover, the baseflow recession analysis was conducted for two different sets of catchments, which were grouped by the location of each catchment relative to the Eagle

Ford play (inside, blue dots and outside, orange dots in Fig. 1). This was done under the hypothesis that for those watersheds located inside the play, the number of recession days for which significant changes are found, will exceed observed changes in the watersheds located outside the play. The flow diagram summarizes all the steps involved to quantify the effects of HF development and climate variability in catchment baseflow (Fig. 2).

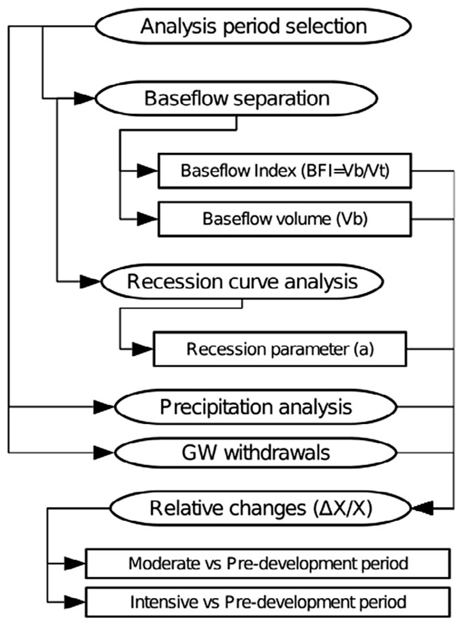

Fig. 2. Conceptual framework showing the methodology employed in this research. The period of analysis ranges for 1980–2015 and separated into three sub-periods: pre-development (1980–2000), moderate hydraulic fracturing (2001–2008) and intensive hydraulic fracturing (2009–2015).

2.4. Impacts of climate variability on baseflow

To separate the effect of climatic variability signals (such as droughts) from HF to changes in baseflow, datasets of precipitation and total evapotranspiration (Livneh et al., 2015) and total water storage anomalies from GRACE (Landerer and Swenson, 2012) were incorporated into our analysis.

To assess the correlation between climate variability and baseflow, relative changes with respect to the pre-development period were compared, where relative changes were calculated as:

$$\left(\frac{\Delta X}{X}\right)_p = \frac{X_p - X_1}{X_1} \quad (3)$$

where X_1 is the variable averaged over the pre-development period, Xp is the variable averaged over the moderate or intensive period, respectively.

3. Results

3.1. Baseflow recession analysis

As expected because of the precipitation gradient increases from west to east, baseflow contributions and perennial streamflow regimes also increase in this direction. A clear example is shown in Fig. 3d, where mean annual baseflow volume (Vb) during the pre-development period low (0–30 mm/yr) in the western part

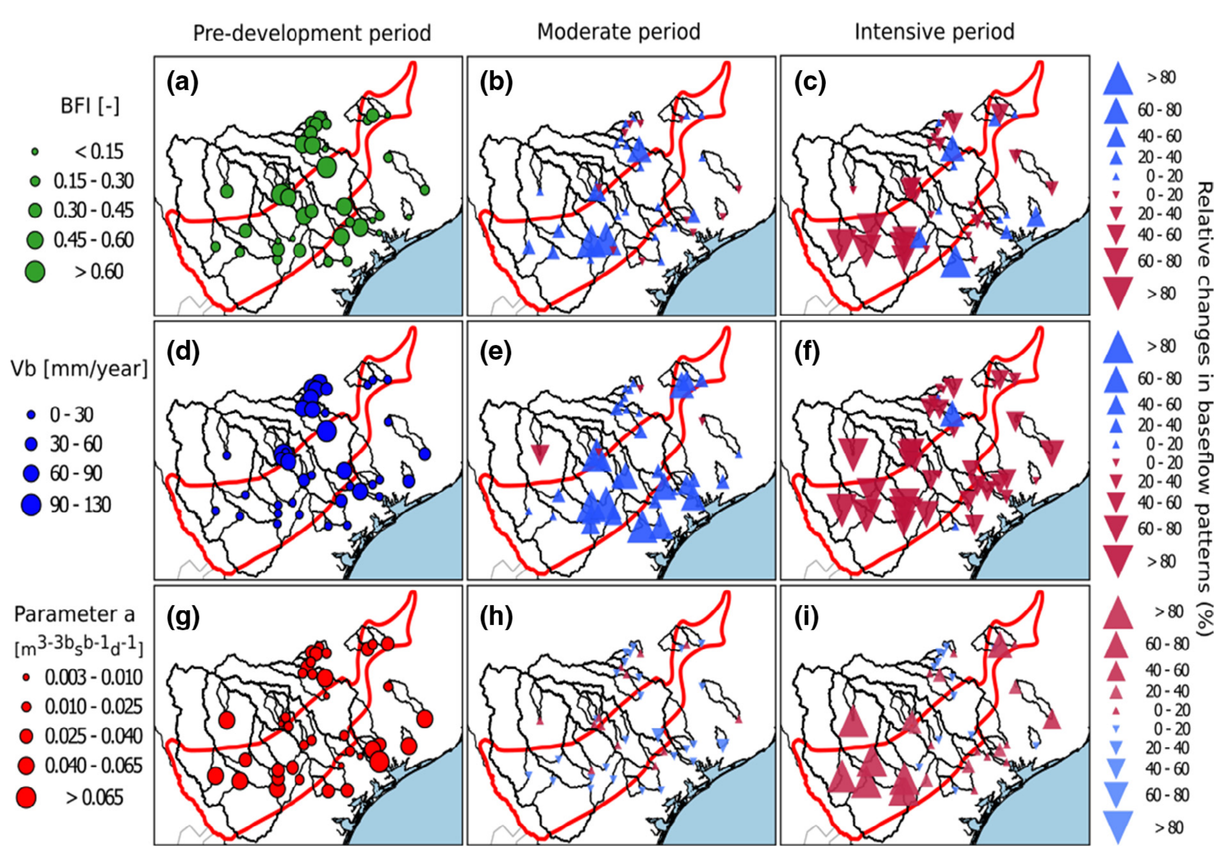

Fig. 3. Relative changes (%) in baseflow patterns for the moderate (middle column) and intensive (right columns) periods, compared to the pre-development period (left column). The size of the triangles represents the magnitude of the change, with blue triangles (upwards) representing an increase red triangles (downwards) indicating a decline with respect to the pre-development period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

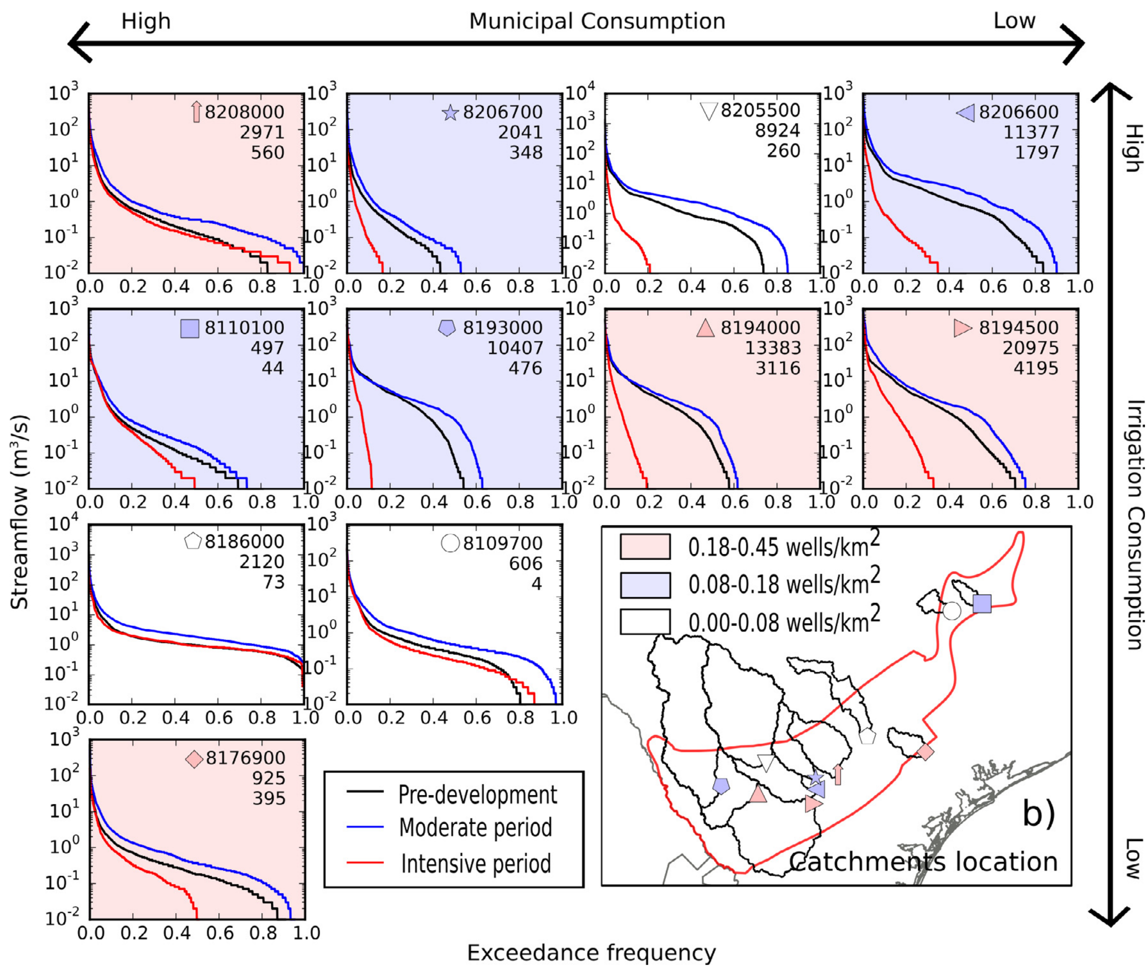

Fig. 4. Flow-duration curves of stream gauges (identified with symbols in the map) located inside the Shale play (each sub-period is displayed by a different color line) during the 3 different stages of HF development. Plots were sorted by mean annual groundwater municipal consumption (columns) and by mean annual groundwater irrigation consumption (rows). The background color in each plot represents the hydraulic fracturing well density by catchment (wells/km2). The legend for each plot indicates the USGS stream gauge code, catchment area (km2) and total number of hydraulic fracturing wells in the catchment.

(small blue dots), in comparison to higher baseflow volumes (60–130 mm/yr) in central-eastern catchments (large blue dots). The link between V_b and BFI is evident as higher V_b volumes in the study region are associated with streamflow regimes dominated by baseflow (Fig. 3a). High V_b values are inversely correlated to recession parameter values a (<0.025), which can be considered a proxy for mild falling recession limbs (Fig. 3g). The relationship between catchment storage (S) and discharge (Q_b) was found to be predominantly linear (b = 1) in the northern catchments located south of the Edwards and Trinity aquifers, whereas a quadratic relationship ($S^2 \sim Q_b$) characterized baseflow patterns across eastern catchments (with b ~ 1.5), fed by the Carrizo-Wilcox and Gulf Coast aquifers. In western catchments connected to the Edwards and Carrizo-Wilcox aquifers, the value of the power law exponent is ~0.5.

The response of baseflow patterns such as BFI (Fig.3b) and V_b (Fig.3e) to moderate hydraulic fracturing activities was substantial in relative terms (an increase of at least 60%). Likewise, the response of baseflow recession timing (parameter a) to shale development has a limited or unnoticeable effect (Fig. 3h). In contrast, the anticipated response of baseflow to intensive HF was found to be clear (Fig. 3c, f and i) when compared to the baseline pre-development period. Overall, a significant decline of ~80% or more for BFI and V_b, and a similar rise of parameter a (shorter and steeper recession times, and hence more intermittent and ephemeral stream flows) were observed within the Eagle Ford play. Nevertheless, in catchments located outside the play, a similar behavior was observed as baseflow volumes also experienced a decline in the same order between 40–60% (Fig. 3f).

3.2. Impacts of hydraulic fracturing on baseflow

Consideration of other water demands on baseflow should allow us to identify the primary drivers of the observed temporal changes in baseflow patterns. Catchment 8206700 has the highest irrigation pumping rates, ~40 times greater than irrigation demand in catchment 8176900 which has the lowest pumping rate or irrigation rate (Fig. 4). Similarly, catchment 8186000 has an irrigation pumping rate ~60 times the municipal pumping rate for catchment 8194500. Catchment 8162600 has an irrigation pumping rate ~250 times higher than that catchment 8158810 (Fig. 5). Finally, catchment 8178656 has a municipal pumping rate ~90 times relative to that in catchment 8189700.

Changes in streamflow were also related to drainage area. Catchments larger than 8000 km^2 with high irrigation groundwater use for irrigation and high HF well density show steep declines in the flow duration curves. Moreover, intermittent flow catchments in the southwest region show a decline through time in baseflow close to 80%, with an increase in intermittency in several catchments (8/11) between 32% and 72% from the baseline to the intensive period, suggesting a link between the long-term aridity conditions and catchment response to groundwater withdrawals.

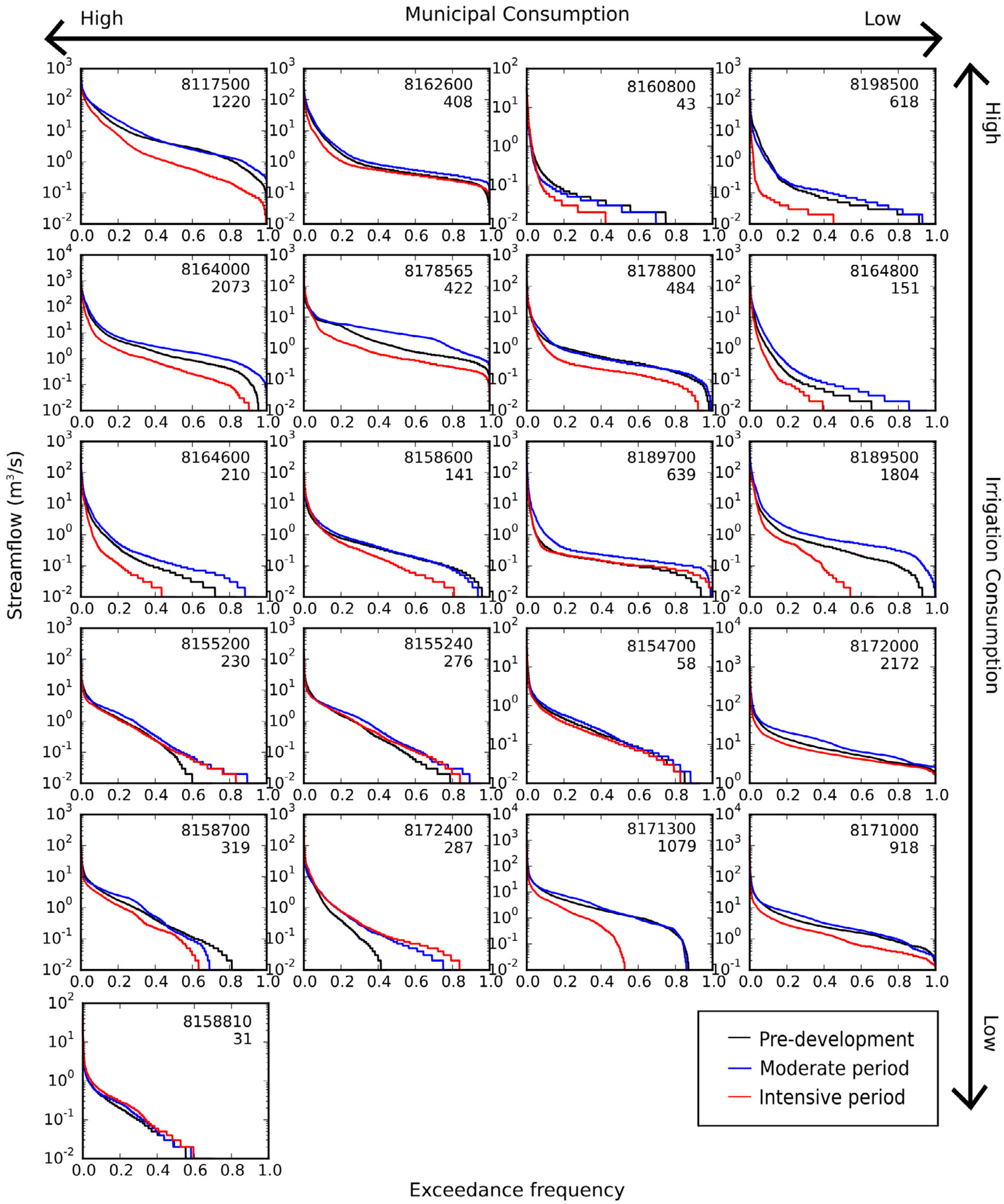

Fig. 5. Flow-duration curves of stream gauges located outside the Shale play (each sub-period is displayed by a different color line). Plots were sorted by mean annual groundwater municipal consumption (columns) and by mean annual groundwater irrigation consumption (rows). The legend for each plots indicates the USGS stream gauge code, catchment area (km2) and total number of hydraulic fracturing wells in the catchment.

In all catchments, the observed decline from the moderate HF time period (2001–2009) to the intensive HF time period, indicates a complex aggregation of water demands which are observed in the streamflow availability.

For comparison, a similar analysis conducted in 21 catchments outside the Eagle Ford shale play shows that 13 stream gauge sites register declines during the intensive HF period (2009–2015), but no significant changes during the moderate HF period (2001–2008) (Fig. 5). During the moderate period, several catchments underwent a reduction in intermittency, from a mean value of 10–6%, though this percentage increased to 17% during the intensive period. Among the study sites with the largest change, catchment 8171300 has the largest increase of Q = 0 from 11%/yr to 46%/yr from the pre-development until the intensive period.

Overall, the most affected catchments show negative changes in V_b up to 60%. Evidence from previous studies suggests that agricultural water use is the primary driver for decreasing groundwater levels and baseflow (Nicot and Scanlon, 2012).

This can be explained by the fact that groundwater withdrawals for irrigation purposes dominate the water use at the Eagle Ford play (~65% of the total water use), followed by municipal and hydropower (Scanlon et al., 2014a). The importance of agriculture in counties outside the shale play becomes less relevant so that the water stress is usually lower in these catchments (Fig. 6). In addi-

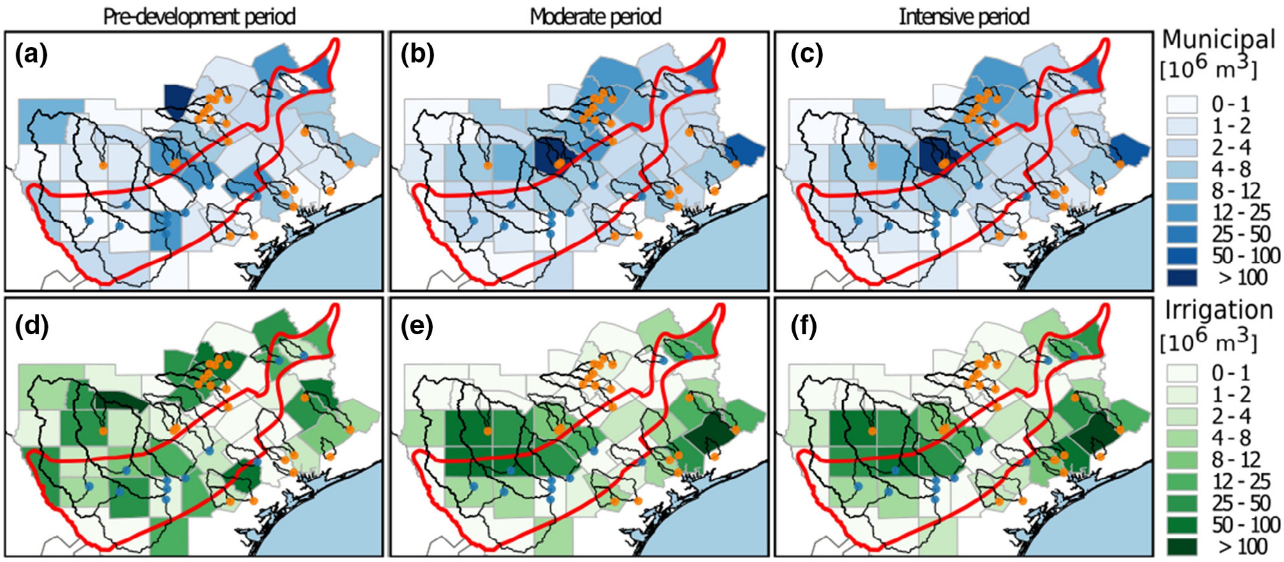

Fig. 6. Mean annual groundwater municipal (top panels) and irrigation (bottom panels) withdrawals by county during each sub-period. Dots correspond to streamflow gauges inside (in blue) and outside (in orange) the Eagle Ford play. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

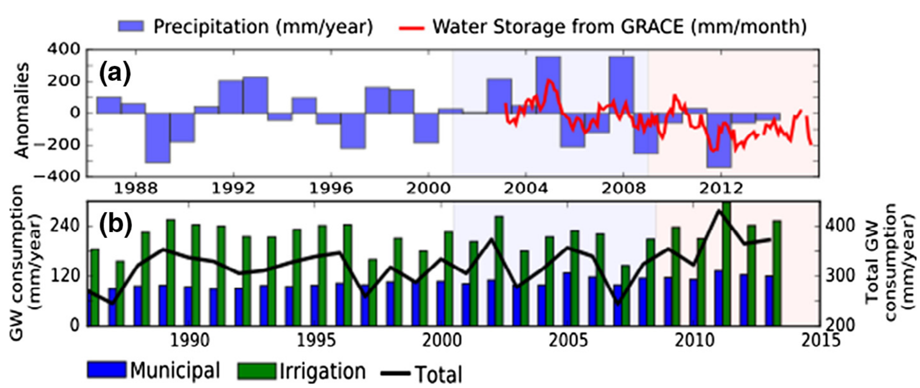

Fig. 7. a) Annual precipitation anomalies and monthly GRACE-derived total water storage anomalies; b) groundwater municipal and irrigation withdrawals for the Eagle Ford Shale play region. Total consumption (black line) considers only municipal and irrigation water use. Color backgrounds in blue and orange correspond to the moderate and intensive hydraulic fracturing periods, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

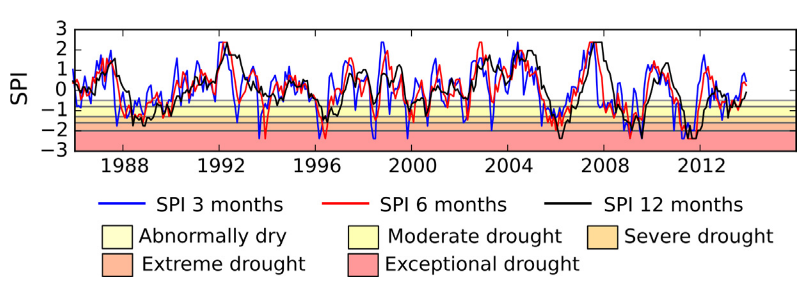

Fig. 8. Spatially-average time series of the Standardized Precipitation Index (SPI) for the Eagle Ford shale play over different time scales: 3-months (blue line), 6 months (red line) and 12-months (black line). Shaded areas represent the severity drought levels (from abnormally dry until exceptional). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tion, urban water demand has strongly risen over the moderate and intensive periods, thus, the contribution of agricultural activities on water stress has become less important over the last decade (TWDB, 2012).

3.3. Impacts of climate variability on baseflow

The intensive HF period overlapped one of the most severe droughts that affected Texas to date (Folger and Cody, 2014; Scanlon et al., 2013). The magnitude of the Texas drought of 2011–2012 (Scanlon et al., 2013; Scanlon et al., 2014a) is characterized by not only negative precipitation anomalies (Fig. 7a), but also significant hydrological deficits (Fig. 7b) and a rise in groundwater withdrawals in some regions (Fig. 7c). These hydrological conditions associated with drought, in combination with an increase in both groundwater abstraction and HF water demands, may have resulted in significant stress to catchment baseflows.

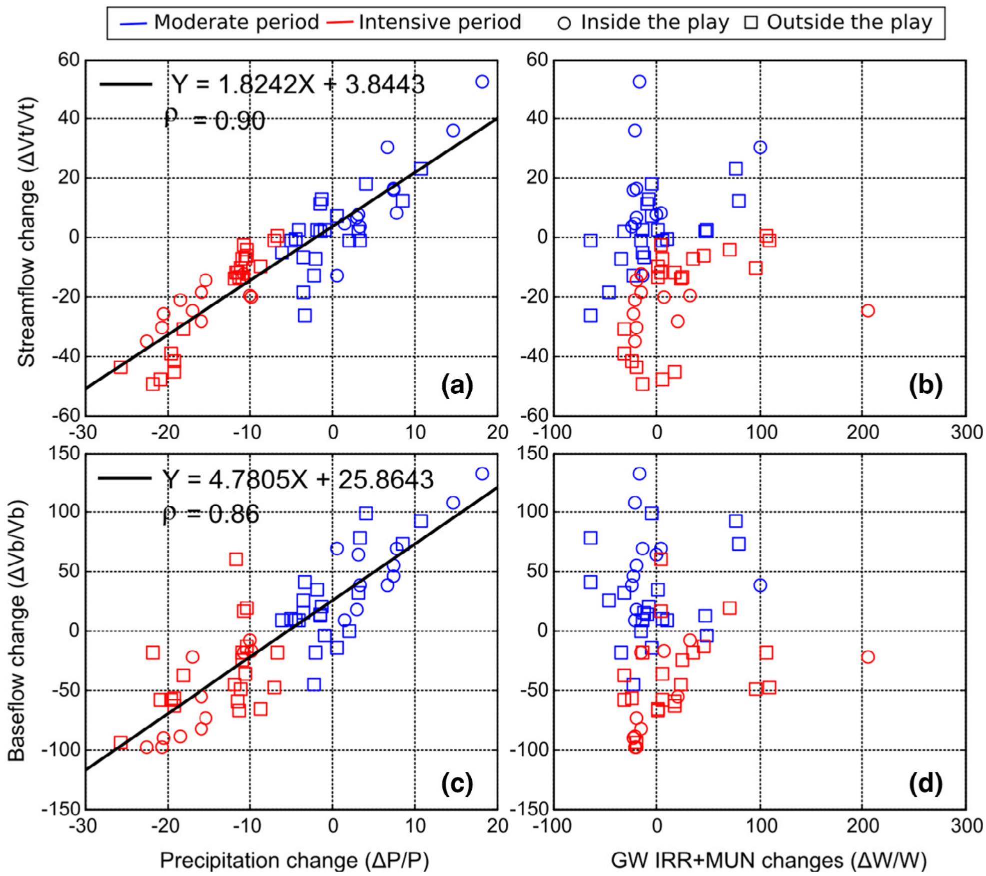

Fig. 9. Statistical correlation of relative changes (%) of a) precipitation vs streamflow, b) irrigation + municipal groundwater withdrawal vs streamflow, c) precipitation vs baseflow and d) irrigation + municipal groundwater withdrawal vs baseflow. Circle dots represent catchments inside the play and square dots catchments outside the play. Blue dots indicate relative changes of the moderate period against the pre-development period and red dots indicate changes of the intensive period with respect to the pre-development period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Indeed, the exceptional severity of the 2011 drought across the region covering the Eagle Ford play footprint is expressed as negative Standardized Precipitation Index values over different time-scales (Fig. 8). As noted, during 2011, the three different SPIs reached the exceptional drought threshold, while in previous years (e.g. 2006), such threshold values were only observed by SPI-12.

Relative changes in precipitation (ΔP/P) are strongly linked to relative changes of streamflow ΔVt/Vt (Fig. 9a) and baseflow ΔVb/Vb (Fig. 9c), with correlation coefficients of 0.90 and 0.86, respectively. In particular, baseflow was observed to be more sensitive to precipitation (~5 times, according to the linear fit of Fig. 9a) than streamflow (~2 times, Fig. 9c), that is, an increase of 20% of precipitation leads to a streamflow increase of 40%, whereas baseflow increases 100%. These results emphasize the sensitivity of catchment discharge to drought-induced low groundwater recharge rates, such as reported by Long et al. (2013) that during the 2011 Texas drought, the lowest baseflow values since 1985 were recorded in the region, mainly attributed to a decline in groundwater storage (Fig. 7b), and soil moisture to a lesser extent.

In contrast, groundwater withdrawals for agricultural and municipal uses did not show a clear relationship with streamflow (Fig. 9b) and baseflow (Fig. 9d) changes. During the moderate period, only 25% of the catchments located outside the play had increases in groundwater demands with respect to the baseline, with only catchment 8110100 inside the play having a relative demand increase of 100 %. In such cases, it is clear that the positive ΔP/P was significantly higher than the groundwater demands, leading to an increase in streamflow and baseflow (Fig. 9b and d). In contrast, catchments that had a decline in precipitation and groundwater demands, also experienced an increase in baseflow, indicating that groundwater demands also contribute to the temporal patterns in baseflow (Fig. 9d).

4. Discussion

4.1. Baseflow recession analysis

Relative observed changes in baseflow (V_b) and its contribution to total streamflow (BFI) do not consider possible existing trends during the pre-development baseline period, that could affect the results in the subsequent analysis periods. Nevertheless, as shown in recent studies, no consistent annual or seasonal trends in baseflow and BFI during the pre-development period were found, with the exception of a couple of catchments that experienced significant positive trends in baseflow during the fall season and BFI during fall and winter (Ficklin et al., 2016), respectively. Results indicate that there are temporal changes in baseflow patterns in watersheds throughout the Eagle Ford play (inside and outside). Therefore, it is necessary to consider different water demands, within these watersheds, associated for example with water supply, irrigation, and HF requirements.

Evidence observed across 8 of the 11 catchments inside the Eagle Ford play suggests that streamflow availability (represented by the flow duration curve for each catchment) declined from pre-development (black lines) towards the intensive period (red lines) (Figs. 4 and 5). The strong decline in total streamflow of these 8 catchments is characterized by steeper slopes of the duration curve. In contrast, the other three catchments reported no reduction in surface water availability (indicated by an arrow, a pentagon and a circle). Notably, in two of these three cases the HF well density is low, which may imply a less important contribution of HF to changes in water availability during the three studied periods. A limited reduction in surface water availability was found between the pre-development time period (1980–2000) and the moderate time period (2001–2008).

4.2. Impacts of hydraulic fracturing on baseflow

Although it has been acknowledged that between 2009 and 2013, ~8300 horizontal wells that were drilled in the Eagle Ford play, it represented only 16% of the total water use (Scanlon et al., 2014a). It can be expected that these numbers will change, as for the next 20-year projections of water use for HF activities, anticipate a seven- or eightfold increase with respect to the current HF water use (Nicot and Scanlon, 2012).

The recovery in the flow duration curve during the moderate period (Fig. 4, black lines) can be partially attributed either to improved groundwater management practices that resulted in a more efficient water use for crop production (Deeds et al., 2003) or more rainfall supply during wet years (Fig.7a).

Although the impact of the 2011–2012 drought on streamflow was not uniform, several catchments (mainly those outside the shale regions) were hardly affected (Fig. 5). Indeed, positive anomalies in precipitation for 2004–2007 could also explain the streamflow recovery observed during the moderate period in 11 and 9 catchments located inside and outside the shale play (see Figs. 4 and 5, respectively).

4.3. Impacts of climate variability on baseflow

This work also highlights the impact of exceptional dry spells on hydrological conditions in water-limited regions. The combination of natural forcings (drought) and anthropogenic activities (HF, irrigation, and municipal use) are the dominant controls on baseflow dynamics across different timescales studied. Spatially-focused shallow groundwater pumping to satisfy croplands and shale gas fields over several years will certainly have a clear impact on streamflow quantiles. However, catchment-scale declines in surface water availability seems to be exacerbated by one or two years of precipitation deficits.

During the intensive period, 10 catchments (out of 21) outside the play and 3 (out of 11) inside the play show an increase in water demands with respect to the baseline. However, catchments with reduction in water demands were more affected by drought (with $-25 < \Delta P/P < -15\%$), and thus, more severe declines in streamflow and baseflow were observed in those catchments.

Nevertheless, the largest volumes of groundwater withdrawals actually show small changes with respect to the baseline, and then, the real impact of pumping was difficult to isolate from other factors. This is the case for catchments outside the play that display higher pumping volumes during the moderate and intensive period and were more likely to have a stronger decline on $\Delta Vb/Vb$ in comparison with catchments with less water stress (see Fig. 9c y d).

However, shale oil/gas development could have consequences for catchments inside the play. For example, pumping in catchment 8110100 increased by twice their agricultural and municipal water demands from the moderate to intensive period (Fig.9d) and experienced a $\Delta P/P$ of -17% and a $\Delta Vb/Vb$ of -22%, while catchment 8176900 (with less pumping for agricultural and municipal use but higher HF wells densities, see Fig. 4) show a similar $\Delta P/P$ but ~40% baseflow reduction (Fig. 9d). Similar results were observed in other catchments with different pumping volumes and similar precipitation changes, overall, those catchments with high HF well densities had steady declines on Vb. Nevertheless, more than two thirds of the catchments inside the play with high HF well densities also had strong negative changes in precipitation ($\Delta P/P < -18\%$) so that the effects of HF were masked by the 2011 drought.

5. Conclusion

This investigation aimed at testing a conceptual framework to quantitatively assess the impacts of hydraulic fracturing activities on baseflow in semi-arid zones. Hydraulic fracturing among other anthropogenic water demands (e.g. agriculture and municipal consumption) exerts an influence, limited in relative terms, on catchment hydrology, which needs to be evaluated.

In order to understand the interactions between water demand for HF and water availability, this study applied a baseflow analysis technique in two sets of unregulated catchments located inside (11) and outside (21) the Eagle Ford play in Texas. The approach considered that within water-limited regions, baseflow may exhibit temporal changes due to adjustments in water demand related to agricultural and municipal sectors and HF activities. Such an approach was tested over three periods of time that were related to HF activities: pre-development (1980–2000); moderate (2011–2008); and intensive (2009–2015).

Results indicate that there are temporal changes in baseflow patterns in the 32 watersheds located across the Eagle Ford play (inside and outside). However, these changes were associated with an aggregated effect, resulting from an exceptional drought in 2011, intense hydraulic fracturing activity (# wells/area), and higher irrigation rates because the majority of catchments located within the Eagle Ford play (8 out of 11), exhibited a substantial decline in surface water (streamflow) availability. However, results for 21 catchments located outside the Eagle Ford play, also registered declines in surface water availability during the intensive HF period (2009–2015), but insignificant changes during the moderate HF period (2001–2008). Moreover, watersheds with the largest declines in surface water availability, were associated with the largest precipitation declines and groundwater consumptive uses.

The drought period was characterized by substantially below average rainfall, historically low GRACE derived water storage anomalies, and high total groundwater demand. As a result, baseflow conditions were negatively affected during 2011, when compared to past streamflow records. Baseflow recession analyses revealed statistically significant changes related to the absolute (Vb) and relative (BFI) contribution of baseflow to streamflow, as well as some of their groundwater hydraulics parameters (a). This analysis highlights the importance of accounting for climate extreme events on drought impacts within a water-energy nexus context.

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(Landerer & Swenson, WRR, 2012) (ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land_mass/RL05/). Information about water use for agricultural, municipal and hydraulic fracturing purposes were by the Texas Water Development Board (http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp) and the US hydraulic fracturing chemical registry website (www.fracfocus.org).

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