Spatiotemporal and stratigraphic trends in salt-water disposal practices of the Permian Basin, Texas and New Mexico, United States

Casee R. Lemons, Guinevere McDaid, Katie M. Smye, Juan P. Acevedo, Peter H. Hennings, D. Amy Banerji, and Bridget R. Scanlon

ABSTRACT

Subsurface disposal of salt water coproduced with oil and gas has become a critical issue in the United States because of linkages with induced seismicity, as seen in Oklahoma and northcentral Texas. Here, we assess the spatiotemporal and stratigraphic variations of salt-water disposal (SWD) volumes in the Permian Basin. The results of this analysis provide critical input into integrated assessments needed for handling of produced water and for emerging concerns, such as induced seismicity.

Wellbore architecture, permits, and disposal volumes were compiled, interpreted for disposal intervals and geologic targets, and summarized at formation, subregion, a 100-mi^2 (260-km^2) area, and monthly volumes for the years 1978–2016. Geologic targets were interpreted by intersecting the disposal intervals with gridded stratigraphic horizons and by reviewing well logs where available.

A total of 30 billion bbl (~5 trillion L) were disposed into 73 geologic units within 6 subregions via 8201 active SWD wells for 39 yr. Most disposal occurred in the Midland Basin and Central Basin Platform (CBP) over the first 34 yr but shifted from the CBP to the Delaware Basin over the last 5 yr (2011–2016) with the expansion of unconventional oil and gas production. Approximately half of the salt water is disposed above the major unconventional reservoirs into Guadalupian-aged formations, raising concerns of overpressuring and interference with production. Operators are exploring deeper SWD targets; however, proximity to crystalline basement poses concerns for high drilling costs and the potential for induced seismicity by reactivation of deep-seated faults.

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INTRODUCTION

Energy and environmental futures depend on water management solutions that strategically account for safe, economic management of oil and gas wastewater. Safe practices are essential for reducing adverse impacts on the environment, including potentially human-induced seismic activity from wastewater disposal (National Research Council, 2013; Ground Water Protection Council and Interstate Oil and Gas Compact Commission, 2017). Before reliable strategies can be developed, a comprehensive understanding of historical wastewater management linked to subsurface geology should be developed.

Produced Water

Oil and gas production generally result in the coproduction of water from the wellbore. This water is primarily briny formation water but may contain some water that was injected into the reservoir for hydraulic fracturing (flowback water) or water flooding. Various terms are used to describe the produced water (PW), including flowback and PW (Nicot et al., 2014), or, in many cases, simply PW (US Geological Survey, 2018). The United States produced an average of 10 bbl (1590 L) of water per barrel of oil in 2012, although PW volumes can range from a few barrels (~500 L) to 200 bbl (~32,000 L) of PW per 1 bbl (159 L) of oil (Veil, 2015). These estimates do not distinguish between PW from conventional, high-permeability reservoirs and unconventional, low-permeability reservoirs. Frequently, PW from conventional reservoirs is managed by injecting it back into the reservoir to maintain reservoir pressure for oil production or to increase oil production using water flooding, both of which we group into the secondary recovery (SR) scheme. Water may also be permanently injected into the subsurface with the intention of not affecting production in any way; we refer to this practice as salt-water disposal (SWD). Studies of PW management practices across the United States show that PW injection was divided almost equally between SR and SWD in 2007 (Clark and Veil, 2009) and 2012 (Veil, 2015).

Underground Injection Control Program

The Underground Injection Control (UIC) Program regulates SWD and SR wells. The UIC Program was established in 1974, when Congress passed the Safe Drinking Water Act (SDWA) as the basis for regulating UIC wells and granted authority to the Environmental Protection Agency (Environmental Protection Agency, 2016). The Environmental Protection Agency has grouped injection wells into six classes (classes I–VI) based on the type of wastewater being injected, thus affecting wellbore design (Clark et al., 2006; Environmental Protection Agency, 2016). All injection wells related to oil and gas activity are class II wells, including SWD and SR. The agency later awarded primacy, or authority to regulate, class II wells to many states under Section 1425 of the SDWA. In 1982, primacy was awarded to the Railroad Commission of Texas (RRC) and the New Mexico Oil Conservation Division (NMOCD) (Environmental Protection Agency, 2018).

Class II Well Types

In this paper, we discuss SWD and SR class II wells, with a focus on SR in the Permian Basin (Figure 1). Texas and New Mexico have different cataloging schemes for class II wells, although both states effectively distinguish SWD from SR. For Texas, we use the RRC typification scheme and consider types 1 and 2 as SWD and type 3 as SR. The RRC type 1 is disposal into a zone not productive of oil and gas; RRC type 2 is disposal into a zone productive of oil and gas; and RRC type 3 is enhanced oil recovery or SR (CDM Smith, 2014; Railroad Commission of Texas, 2014). Because disposal is designed to have no impact on production, type 2 disposal typically occurs in a formation that was formerly productive but is no longer economic in that location. New Mexico has a simpler cataloging scheme of disposal and injection class II well types (New Mexico Oil Conservation Division, 2004), with no distinction between disposal into productive versus nonproductive formations. For simplification, we group Texas' types I and II into the SWD scheme and New Mexico's injection wells into the SR scheme. Texas and New Mexico also permit a variety of other class II well types that are not discussed in this paper.

Texas and New Mexico Permitting Regulations

Texas and New Mexico permitted values for class II wells include maximum wellhead injection pressure, top and bottom depths of injection interval, and packer depth. Other parameters that may be included in the permit are target formation name (Texas and New Mexico), tubing size (New Mexico), permitted fluids (Texas), and casing integrity test frequency (Texas) (New Mexico Oil Conservation Division, 2019; Railroad Commission of Texas, 2019a). New Mexico SWD and SR maximum wellhead injection pressures are permitted at a gradient (psi/ft), and injection depths are permitted top to base, in feet. New Mexico permitted injection pressure may or may not include a maximum pressure value. Texas maximum wellhead injection pressure is permitted at 0.5 psi/ft (3.5 kPa/m) up to the top of the injection interval. The 0.5 psi/ft (3.5 kPa/m) pressure regulation applies across most of the state of Texas with a few exceptions (Railroad Commission of Texas, 2019b), the Permian exception being the Delaware Mountain Group in the Delaware Basin, which is permitted at a maximum wellhead pressure of 0.25 psi/ft (1.7 kPa/m) as of 2019 (A. Rios, 2019, personal communication).

The top and bottom depths of the injection interval are typically applied for and approved at a depth range that is greater than what is used by the wellbore perforation design. Therefore, it is necessary to

and trends. Funding for this project is provided by the state of Texas through the TexNet research collaborative. The software that was used includes IHS Petra version 3.8.3 for the relational database and ArcMap version 10.3.1 for geographical information systems mapping.

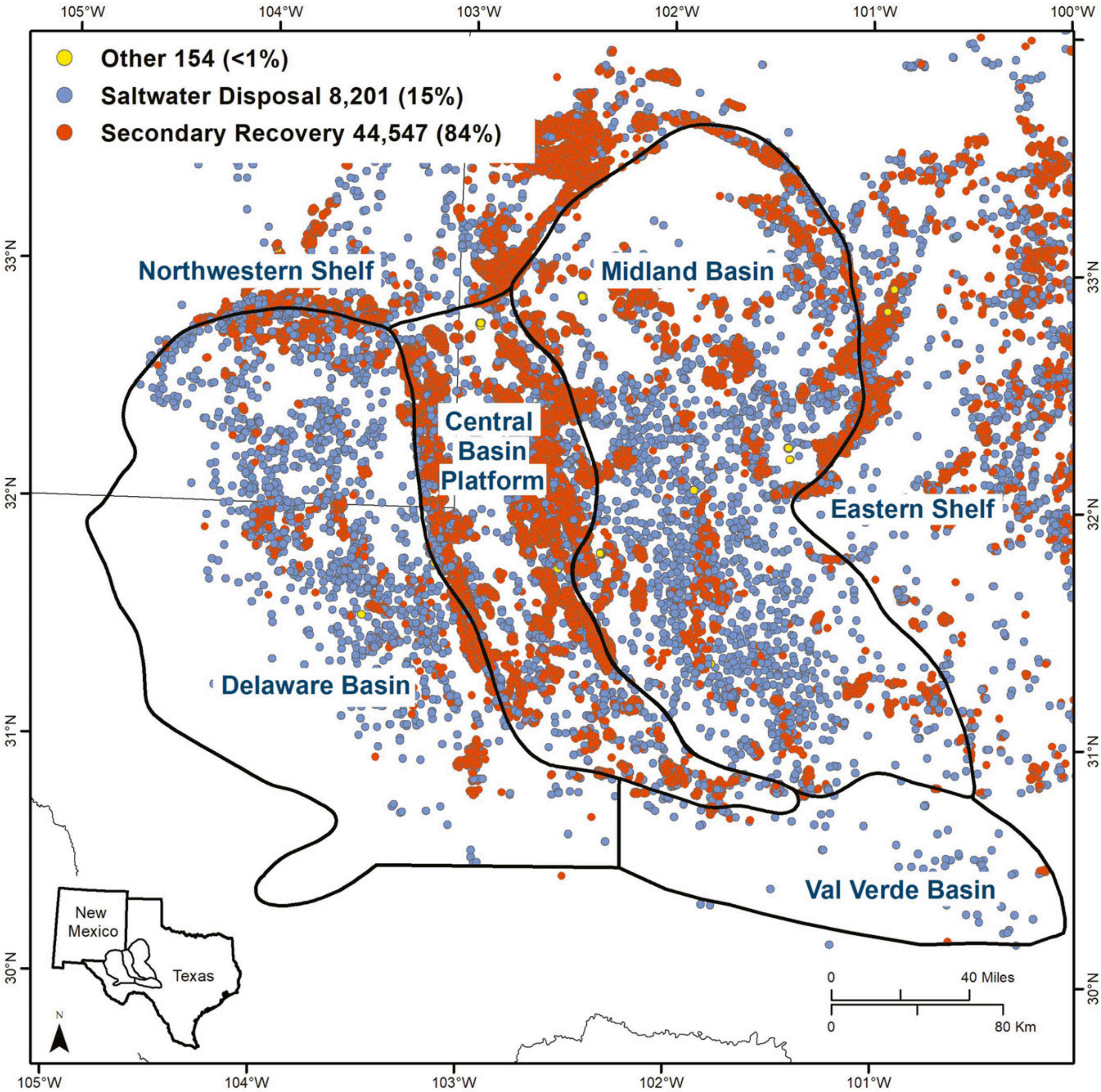


Figure 1. The Permian study has six subregions of focus, with class II wells in the Permian Region actively injecting water any time from 1978–2016. Wells are mapped according to their surface hole location. If a well was active as more than one Underground Injection Control (UIC) class II type, the well is mapped twice. Permits were extracted from the New Mexico Oil Conservation Division and Railroad Commission of Texas websites and are classified by the UIC class II permit types. New Mexico injection wells are combined with Texas secondary recovery wells and are shown in orange.

extract active perforations within the permitted range to ascertain the actual disposal interval. Similarly, the permitted formations cover the entire expanse of the permitted injection interval and the formation name may or may not be included in the permit. To interpret the formation for injection, it is necessary to first extract the active disposal interval and land it inside structural–stratigraphic zones, which we have done in this paper.

In New Mexico, permits are granted depending on whether the targets are noneconomical or noninterfering with production yields; thus, the permitting of certain formations has changed over time. For example, New

Mexico freely permitted disposal into the time-equivalent Delaware Mountain and Artesia Groups until 2010, when New Mexico Administrative Code 19.15.16.15 went into effect. The new "horizontal rule" authorized well laterals to exceed 4500 ft (1372 m) and made these formations newly economical for production, greatly reducing permitting for SWD in the Delaware Mountain and Artesia Groups (P. Goetze, 2017, personal communication). To prevent interference with production, New Mexico is currently not permitting new SWD wells into Guadalupian strata near actively producing locations. New Mexico is no longer issuing any new permits for disposal into the Ellenburger Group to prevent seismicity induced by injection near basement-seated faults (P. Goetze, 2017, personal communication).

Seismicity Associated with Fluid Injection

Because of links to induced seismicity, particularly in Oklahoma, there is increasing concern about the management of PW (Keranen et al., 2013, 2014; Hough and Page, 2015; Walsh and Zoback, 2015). A new classification scheme of induced seismicity has been proposed as those related to oil and gas wastewater fluid injection (Doglioni, 2018). Positive correlations were found between the number of earthquakes, magnitude of earthquakes, and subsurface fluid exchange via SWD wells (Keranen et al., 2014; Hornbach et al., 2015, 2016), SR wells (Improta et al., 2015), hydraulic fracturing wells (Horton, 2012; Maxwell et al., 2015), and oil and gas production wells (Davis et al., 1995; Frohlich and Brunt, 2013). Previous studies have linked SWD-related seismicity to SWD injection rates (Weingarten et al., 2015; Barbour et al., 2017), cumulative SWD volumes (Suckale, 2009; Ellsworth, 2013; McGarr, 2014; Walters et al., 2015), and proximity of the SWD geologic target to the basement (Ellsworth, 2013; Maxwell et al., 2015; Hornbach et al., 2016; Hincks et al., 2018). McGarr's (2014) case history analyses emphasized total volume of fluid injected into the subsurface as the primary determinant of seismicity, whereas other case studies showed rate change as the primary impact factor for inducing seismicity in the midcontinent United States (Weingarten et al., 2015), Osage County, Oklahoma (Barbour et al., 2017), and the Val d'Agri Basin in onshore Europe (Improta et al., 2015). Some studies concluded that both total volume and fluid rates can cause seismicity, as long as those fluids cause the pore pressure at a fault to exceed the critical failure threshold (Keranen et al., 2013, 2014; Improta et al., 2015; Abrahams et al., 2017). An update (Scanlon et al., 2017) of the Weingarten et al. (2015) study added 3.5 yr of Oklahoma data and a new basement map showing that cumulative regional SWD volumes, as well as proximity of SWD to the basement, were all linked to seismicity in Oklahoma. This study shows that limited seismicity in other major unconventional oil plays has been attributed mostly to shallow SWD above the unconventional oil and gas reservoirs in Bakken, Eagle Ford, and Permian Basin plays.

The region around the city of Pecos, Texas, is currently experiencing the highest rate of earthquake occurrences in Texas, greatly exceeding historical rates (Frohlich et al., 2019). Whether these earthquakes are linked to SWD, hydraulic fracturing, oil and gas production, other potential causes, or a complex combination of factors is currently unknown. Areas in the Permian Basin, such as Scurry and Kent Counties, have shown a high potential for fault slip from small pore pressure changes (Lund Snee and Zoback, 2016) that are most likely being induced by oil and gas activities (Davis and Frohlich, 1993; Frohlich et al., 2016), demonstrating the need for quantitative delineation of disposal volumes, both geospatially and stratigraphically. West Texas has experienced an increase in seismicity rates, with as many as 12 events, including earthquakes with magnitudes greater than 3.0, per year since 2008 (Frohlich et al., 2016). According to the scoring and categorization system proposed by Frohlich et al. (2016), this increase in local seismicity in the Permian Basin is almost certainly induced, though the mechanisms remain unknown. The likelihood of seismicity depends on variability in rock properties determined by local geological conditions plus local pore pressure changes and fluid flow, possibly caused by influx of salt water during disposal. Rock properties, such as porosity and permeability, change vertically and spatially across the basin. Therefore, geospatial and subsurface zones will experience varying sensitivity to SWD or SR (Shah and Keller, 2017). It is important to analyze volumes, rates, and subsurface targets of SWD because both geologic character and SWD practices are contributing factors to induced seismicity and are important considerations for future wastewater management.

Study Objectives

The objective of this study was to quantify SWD volumes in terms of the temporal changes related to geography and stratigraphy. The primary driver of this work was to understand net fluid budgets and subsurface capacity because of impacts on pressure and potential links to seismicity. Novel aspects of this work include the extended time period examined (1978–2016), the large number of SWD wells evaluated (8201), detailed evaluation of SWD volumes by mining data from state commissions coordinated with well-specific, quality-controlled monthly SWD volumes, and linking disposal intervals to a three-dimensional stratigraphic model with 73 stratigraphic horizons in the Permian Basin. The stratigraphic column developed in this study was based on several different structural and stratigraphic interpretations (e.g., Jones, 1953; West Texas Geological Society, 1958, 1976; Keller et al., 1980; Hills and Kottlowski, 1983; Dutton et al., 2004; Hentz et al., 2016; Ruppel, 2019). Interpretations of the geologic targets are much more highly resolved vertically and horizontally than in previous analyses. This study analyzes a longer time period and interprets stratigraphy at higher resolution than the recent reconnaissance analysis of SWD in the Permian Basin related to general disposal intervals (shallow, intermediate, and deep) in producing intervals over a short time period (2008–2016) (Scanlon et al., 2017, 2018). The results presented in this study are more detailed than any single-year analysis (Murray and Holland, 2014), 5-yr analysis into 12 stratigraphic zones (Murray, 2015), or statewide analyses of estimated injection volumes and permit type distributions (Clark and Veil, 2009; Veil, 2015).

METHODS

The Permian Basin is divided into six subregions: the Northwestern Shelf, Delaware Basin, Val Verde Basin, Central Basin Platform (CBP), Midland Basin, and Eastern Shelf (Figures 1, 2A). Within each subregion, a stratigraphic correlation chart (Figures 3A; 4; 5) was developed based upon the following: (1) previous structural and stratigraphic work; (2) operator-reported naming conventions of formation tops reported in W-2 completion forms from the RRC; and (3) structural–stratigraphic grids of Bureau of Economic Geology researcher top picks, log tops, and operator-reported tops. The spatiotemporal distribution of SWD volumes in each subregion is shown in Figure 2B.

Permits from the UIC from the New Mexico Oil Conservation Division (2019) and Railroad Commission of Texas (2019a) were placed into a relational database software using the 10-digit API number as primary key. A total of 8201 SWD wells were actively disposing fluids into the subsurface from 1978 through 2016 in the Permian Basin. Quality control for data entry errors included comparison of monthly disposal volumes with average and maximum wellhead pressures with a graphic overlay of each data set. Disposal depth intervals and associated geologic targets were identified using a combination of permit parameters, structural–stratigraphic grids, and lease depths. If multiple formations were targeted for disposal in a single well, volumes were normalized across the targets according to the count of formations intersecting the disposal interval. Annual and cumulative volumes were mapped within 100-mi^2 (260-km^2) grid blocks.

Disposal intervals were identified for each SWD and SR well. Disposal intervals are not readily available from any one source, but they are interpreted based on large data sets, quality control, and per-well evaluations. The disposal depth intervals were selected by integrating the wellbore's history, including drilling, completions, and permit histories with 73 structural–stratigraphic grids and operator-reported formation tops and nearest-neighbor correlations. Structural–stratigraphic horizons were created across the six subregions to compute the structural thickness of SWD target zones. Approximately 765,000 well-based formation tops were used in grid construction via a prioritized ranking system based upon the stratigraphic picks of internal researchers, commercial tops, and operator-reported tops. Interpretation of the disposal interval was based upon extraction of active perforations within the wellbore's completion history of each well to match with the H10 annual reported depths (Texas), permitted depths (Texas and New Mexico), and/or test depths (New Mexico). The disposal top and bottom, typically a subinterval of the permitted depth range, were selected as the most accurate representation of the wellbore's currently active perforation scheme. Where available, Delaware Mountain Group well logs were used to confirm disposal into the Delaware Mountain Group in the Delaware Basin. Structural–stratigraphic contour surfaces for each formation were created and then were sampled to SWD wells. Interpreted disposal depths were landed inside the contours to evaluate which formation(s) were being actively disposed into.

A generalized chart of the stratigraphic interval of disposal across the Permian Basin was colored by the total volume disposed from 1983–2016 (Figures 3, 4).

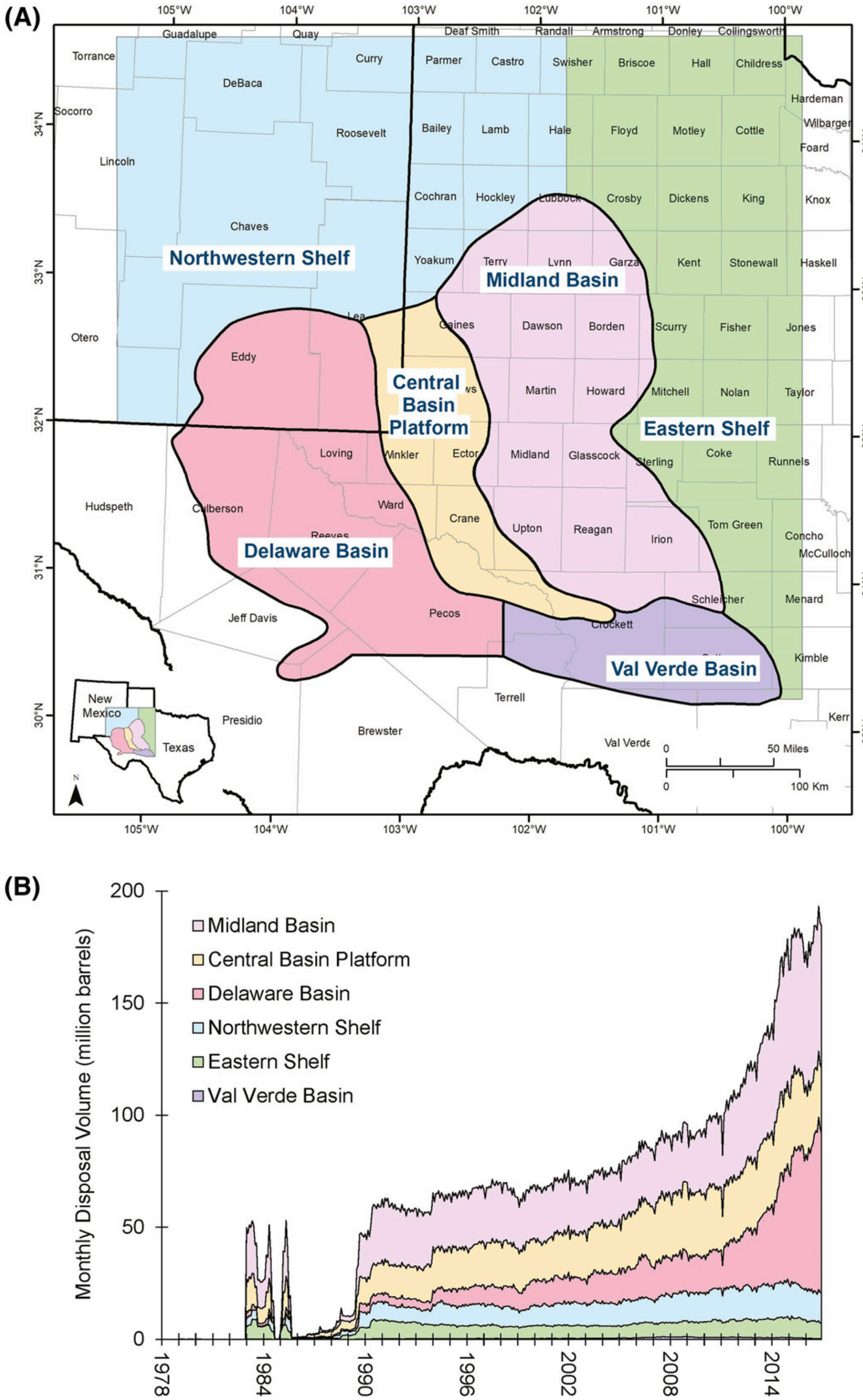


Figure 2. (A) Permian subregions. The subregion color scheme acts as a location reference guide throughout the images. (B) Quality-controlled monthly salt-water disposal volumes (1978–2016) are stacked in order with highest total volume (Midland Basin) on top to lowest total (Val Verde Basin) on bottom.

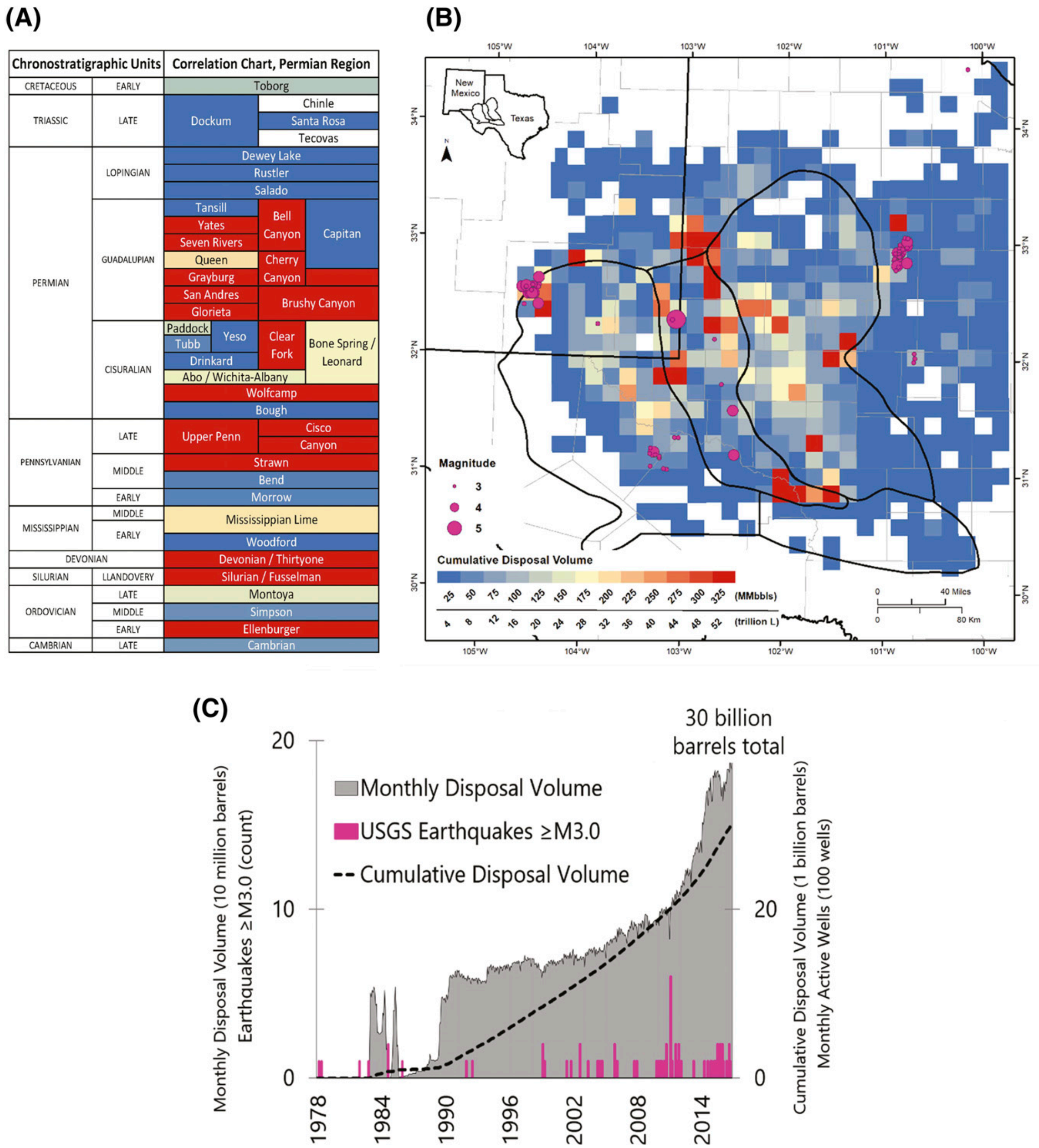


Figure 3. Geographic, geologic, and temporal variation in salt-water disposal (SWD) activity for the Permian Region, Texas, from 1983–2016. (A) Cumulative disposal volumes (1983–2016) are differentiated into 40 major geologic targets using the cumulative disposal volumes color scale, for which blue indicates the lowest volume and red indicates highest volumes. (B) Cumulative SWD volumes are mapped in 100-mi^2 (161-km^2) block grids using the same color scale. (C) Time series chart with monthly SWD volumes (gray area) and monthly active well counts overlain by monthly earthquake counts (magenta) and running cumulative disposal volume (dash). USGS = US Geological Survey.

Formation names shown on the chart were selected from the current naming conventions of operators and regulators to generate a practically applicable use. Common-use names, or those recorded during permitting and drilling, were retained and preferentially used for the chart. Local formation names or archaic reservoir descriptors (e.g., “6250 sand”) were reclassified according to the most common equivalent formation in the subregion. Most formation classifications were straightforward, with the exception of the Cisco, Canyon, and Strawn Groups in the Eastern Shelf, which are permitted for SWD into 25 different members. For simplicity, the 25 members were reclassified into their parent Cisco, Canyon, or Strawn Groups for Figure 4; these groups are expanded to show differentiation into the 25 permitted members in Figure 5. Formation block heights within the correlation chart indicate the relative depositional time span and formation age, not formation thickness. Each formation name block is filled with a color scale that represents the cumulative colors in the correlation chart range blue to red in a heat-style scale.

Cumulative SWD volumes were allocated into each SWD target and shown within the stratigraphic correlation chart using a color scale that matches the geographic distribution of volumes seen in the maps. The SWD volumes were mapped using 100-mi^2 (260-km^2) block grids. Disposal wells were spatially assigned to the 100-mi^2 (260-km^2) block grids using a spatial join using geographic mapping software. Total cumulative disposal volumes per well for each block were then calculated. Disposal volume maps were colored by cumulative volumes spatially distributed across blocks. Temporal variation in SWD volumes is shown in Figures 3B and 6. Monthly SWD volumes were plotted across time, along with monthly active SWD well counts and cumulative disposal volumes. A monthly count of earthquake occurrences (US Geological Survey, 2019) was overlain with the monthly SWD volumes in Figure 3C. All maps created for the purpose of this research were done using ArcMap 10.6. Maps were projected in NAD 1927 StatePlane Texas Central FIPS 4203 coordinate system.

SPATIOTEMPORAL TRENDS OF SALT-WATER DISPOSAL

From 1978–2016, 30 billion bbl (~5 trillion L) were disposed into 73 stratigraphic horizons of the Permian Basin via 8201 SWD wells (Figures 3A; 4; 5; Table 1). The early data from 1978–1982 are limited to New Mexico because monthly reporting was not required in Texas during time (Figure 6). Most disposal occurred in the Midland Basin and the CBP over the first 35 yr but shifted by decreasing in the CBP and increasing in the Delaware Basin over the last 5 yr (2011–2016, Figure 2B) because of the expansion of unconventional oil and gas production. Low volumes from 1986–1989 (Figure 6) reflect the 1980s oil bust, with a maximum decline of 91% in 1986 from the previous peak in 1985. Large SWD volumes in the Midland Basin and CBP from 1983–2010 (Figure 2B) reflect produced wastewater from conventional production. Beginning in 2010, production unconventional reservoirs via lateral wells resulted in large SWD volume increases (Figure 6) locally in the Delaware and Midland Basin centers (Figure 2B). Volumes of SWD in the Northwestern and Eastern Shelves have been generally constant over time (Figure 2B). New Mexico’s recent reduction in SWD permitting into the strata of Guadalupian age and the Ellenburger Group is seen as a slight drop in activity in the Northwestern Shelf (Figure 2B). Activity in the Val Verde Basin shows small, constant disposal volumes from 2006–2016 (Figure 2B) because of low production activity in the Val Verde.

Cumulative disposal volumes from 1978–2016 were mapped in 100-mi^2 (260-km^2) blocks and across time (Figure 3B, C). The highest volumes of cumulative SWD lie near the margins of the Delaware Basin, CBP, and Midland Basin (Figure 3B). The Eastern Shelf and Northwestern Shelf have high SWD volumes along the shelf margins that decrease away from the basins; the Northwestern Shelf shows decreasing volumes south to north, and the Eastern Shelf shows decreasing volumes west to east. Cumulative SWD volumes are displayed in the stratigraphic column that indicates the lateral variation of disposal in chronostratigraphic time.

In the New Mexico part of the Delaware Basin, SWD into Guadalupian strata has been constant because of conservative permitting, whereas Texas disposal into Guadalupian strata is increasing rapidly in Texas. Increasing SWD volumes in the Delaware Basin since 2011 (Figure 2) can be almost entirely attributed to SWD into Guadalupian strata within Texas. However, New Mexico is currently not permitting new SWD wells into Guadalupian strata near active production areas, nor is it issuing any new permits for disposal into the Ellenburger Group (P. Goetze, 2017, personal communication).

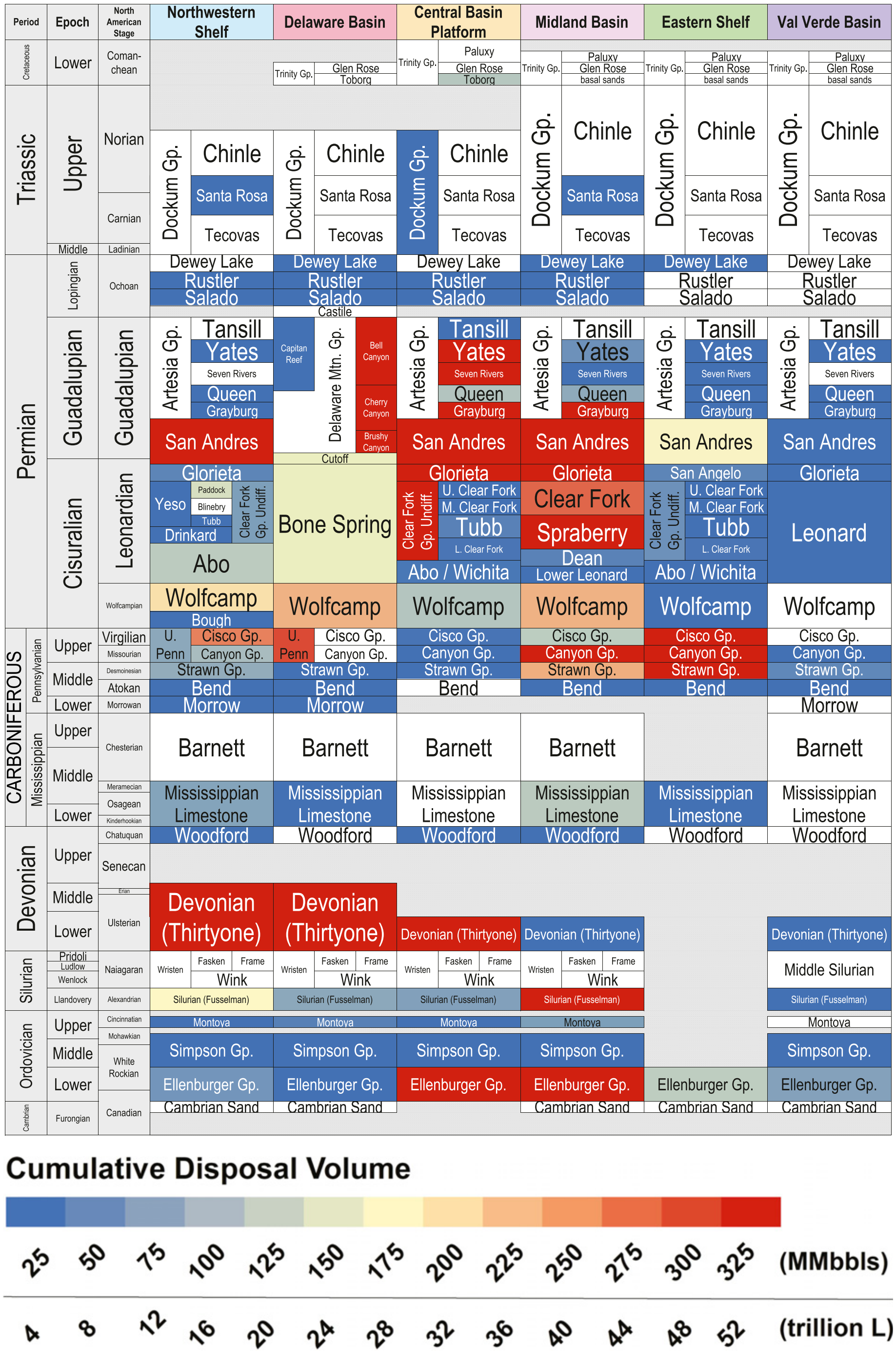


Figure 4. Stratigraphic correlation chart with disposal targets within each Permian subregion. Subregion colors in the header correspond to the map colors in Figure 2. Colors indicate disposal volume in million barrels; white indicates no volume; gray indicates no formation deposition; height of block indicates time of deposition; Cambrian base is cropped. The color scale is shown for 1978–2016 cumulative disposal volumes. The volumetric color scale used in block maps in Figure 3A and B is the same volumetric color scale used in the stratigraphic correlation chart shown in Figures 5 and 6. Modified from Jones (1953), West Texas Geological Society (1958, 1976), Iglehart (1967), Keller et al. (1980), Galloway et al. (1983), Hills and Kottlowski (1983), Childs (1985), Ward et al. (1986), Olson and Johnson (1993), Powers (1993), Grant et al. (1994), Yang and Dorobek (1995), Montgomery (1996), Murphy and Salvador (1999), Christmann (2004), Dutton et al. (2004), Lucas (2004), Broadhead et al. (2005), Menning et al. (2006), Ruppel (2008, 2019), Hamlin and Baumgardner (2012), LimaNeto and Miságio (2012), Walker et al. (2013), and Jones (2016). Gp. = Group; L. = Lower; M. = Middle; U. = Upper; Undiff. = Undifferentiated.

Salt water coproduced from unconventional oil and gas reservoirs is disposed into SWD targets that have considerably higher permeability as compared to the ultra-low native permeability of the producing intervals (Scanlon et al., 2017), whereas SWD on the basin margins may or may not target the same high permeability horizon as the conventional oil- and gas-producing reservoirs. Unconventional reservoirs in subbasin centers marked a transition from uneconomic to economic production via the technologies of hydraulic fracturing and long lateral wells beginning in the mid-2000s. The highest SWD volumes are clustered along subbasin margins coincident with conventional oil and gas reservoirs. Conventional oil and gas reservoirs have been targeted for production and thus had the longest time producing wastewater in need of disposal. Lesser amounts of disposal occurred geographically near unconventional oil and gas reservoirs of subbasin centers between 1978 and 2016, although the volumes observed in basin centers have been disposed mainly since the advent of lateral wells targeting unconventional reservoirs. Wastewater from these unconventional reservoirs is convenient and less costly to dispose of in shallower formations. Disposal on the Northwestern Shelf has been mostly consistent, but decreased since 2015 because of more conservative permitting. Disposal in the Val Verde Basin and on the Eastern Shelf have been steady over time because of relatively low associated volumes of oil and gas. Cumulative SWD volumes in basin centers are midrange yellows (125–225 million bbl [24–36 trillion L]), in contrast to the high-range orange and red blocks (>250 million bbl [>40 trillion L]) in basin margin shelf facies and the blue blocks (<50 million bbl [<8 trillion L]) in low-productivity areas (Figure 3B).

STRATIGRAPHIC TRENDS OF SALT-WATER DISPOSAL

Seventy-three stratigraphic horizons aged Cretaceous to Cambrian have been used for disposal in the Permian Basin (Figures 4, 5; Tables 1, 2). A detailed assessment of disposal formations was performed to determine the cumulative disposal volume into each formation from 1978–2016. Approximately 99% of SWD wells in the Permian Basin target Permian- to Cambrian-aged formations, with less than 1% targeting Triassic- or Cretaceous-aged formations (Table 1). The Eastern Shelf is the only region in the Permian in which individual members of the Cisco, Canyon, and Strawn Groups are permitted for SWD and may be permitted as independent geologic targets (Figure 5; Table 2).

Subsurface targets for SWD are selected based on justification of economic need, target zone porosity, location, cost, and permitting regulations. Currently, the two targets of highest interest are the shallow Guadalupian-aged formations and the deeper Ordovician Ellenburger Group (Figures 3A; 4; 7). Disposal into high-porosity Guadalupian facies (Grant et al., 1994; Dutton et al., 2004) has transitioned from a spatially uniform areal distribution in 1983 to a concentration of high-volume activity within the Midland and Delaware Basin centers (Figure 7). This transition is caused by the growth of the unconventional Spraberry, Wolfcamp, and Bone Spring plays. These tight formations produce large volumes of water that are then disposed into these basin centers producing water that is mostly disposed into SWD wells at a shallower zone than the production zone (Scanlon et al., 2017). The average cost of a new SWD well into Guadalupian strata at a 30,000 bbl/day (~5 billion L/day) capacity is now US$2–$4 million (Spicer, 2018), and wells that were already drilled for production but are no longer economically productive can be recompleted in shallow Guadalupian strata at the cost of plugback and completion only. Guadalupian strata are experiencing localized interference with production, overpressuring, and the potential for exceeding local storage capacity within the formation. Midland Basin operators are reporting increased water cut (PW/(PW + oil)) in oil and gas wells attributed to SWD fluids reemerging with production (Hunter and Lowry, 2018; Wood MacKenzie, 2018). The highest-growth region of SWD into Guadalupian strata is near the city of Pecos in the Delaware Basin (Figure 7), a region that is also experiencing the highest number of earthquakes across Texas. Active investigations are underway to identify the cause of the rapid increase in seismicity near Pecos, for which SWD activity into the Delaware Mountain Group has been named a potential cause.

Operators report exploration of the Ellenburger Group as an alternative to Guadalupian disposal (Figure 7). The Ellenburger Group has long been a target for SWD across Texas and Oklahoma because of its karsted horizons and secondary porosity because of dolomitization (Amthor and Friedman, 1991). The average cost of a new Ellenburger Group SWD well in the Midland or Delaware Basin is much higher, being anywhere from US$14–$22 million (Spicer, 2018), and

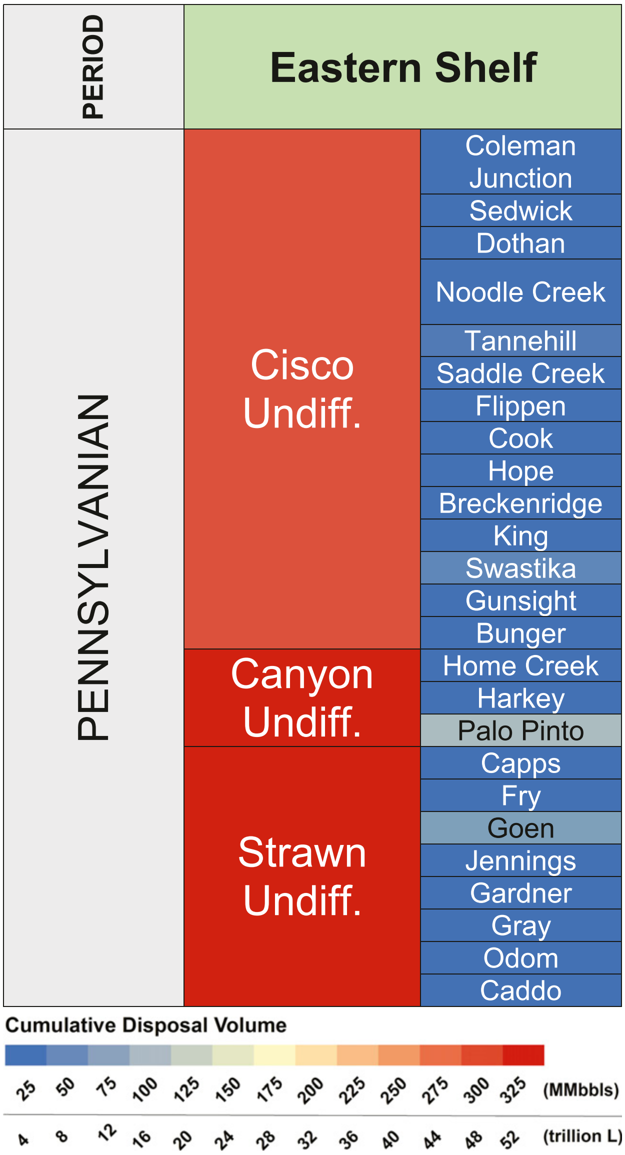


Figure 5. Cisco, Canyon, and Strawn Groups in the Eastern Shelf, expanded to show disposal into specific members. The Eastern Shelf is the only region in the Permian in which members of the Cisco, Canyon, and Strawn Groups are individually permitted for salt-water disposal (SWD) and act as independent geologic targets. The volumetric color scale used in block maps in Figure 3A, B is the same volumetric color scale used in the stratigraphic correlation chart shown here and in Figure 4. The SWD volumes of the members do not equal the volumes of the undifferentiated (Undiff.) groups. The total volume of the Undiff. group and the members are presented as a single sum in Figure 4. Modified from Wright (2008); Holterhoff et al. (2013); and Hentz et al. (2016).

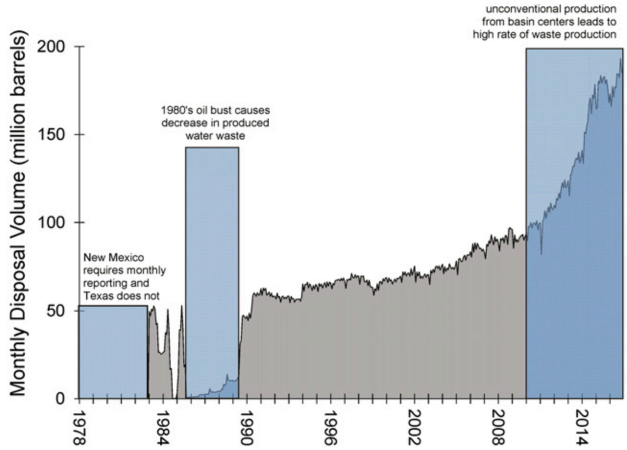


Figure 6. Cumulative disposal over time in the Permian Basin (1978–2016). Notable periods of change are highlighted.

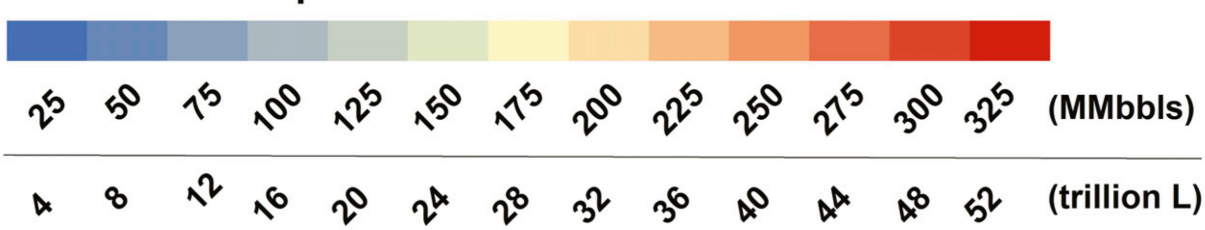
the Ellenburger Group or deeper production wells are less abundant and generally must be newly drilled or deepened for the purpose of disposal. Ellenburger Group SWD drilling has historically been focused on the CBP and Eastern Shelf, where the Ellenburger Group is shallower and less expensive to drill than the deeper drilling required in the Midland and Delaware Basins (Figure 6B). However, the close proximity of the Ellenburger Group to the crystalline basement suggests an associated risk of seismicity by reactivation of deep-seated basement faults via a fluid–fault connection, as seen in the Dallas–Fort Worth area (Hornbach et al., 2015, 2016; Hennings et al., 2019), as well as in the equivalent Arbuckle Formation in Oklahoma (Murray and Holland, 2014; Yeck et al., 2016).

The preferred disposal targets for permitting in New Mexico are the Devonian and Silurian formations, a response rooted in an absence of observed interference with production and no historical associations with induced seismicity in these zones (P. Goetze, 2017, personal communication). The capacity for disposal into Silurian strata on the Northwestern Shelf has been reported by operators to exceed the capacity available in other SWD targets on that shelf. Silurian and Devonian formations are shallower on the Northwestern Shelf than in the Delaware Basin, making them economically viable drilling targets, whereas on the Eastern Shelf, the Pennsylvanian-aged Cisco, Canyon, and Strawn Groups are the primary targets, where wells may target the undifferentiated Cisco, Canyon, or Strawn Groups or individual members (Figure 5; Table 2). The Eastern Shelf is the only subregion where operators target

Table 1. Permian Volumes

Injection Stratigraphy	Northwestern Shelf	Delaware Basin	Central Basin Platform	Midland Basin	Eastern Shelf	Val Verde Basin
Abo	113		31		13	
Bell Canyon		1708				
Bend	0	1		1	20	3
Bone Spring		155				
Bough	8					
Brushy Canyon		399				
Cambrian				9	52	0
Canyon Gp.	98		17	526	469	19
Capitan		5				
Cherry Canyon		1515				
Cisco	264		28	116	507	
Clear Fork Gp.	69		398	280	55	
Dean				42		
Devonian	1242	1210	740	882	1	1
Dewey Lake		0		8	1	
Dockum Gp.			2			
Drinkard	22					
Ellenburger Gp.	59	11	1157	494	117	72
Fusselman	175	77	70	578		15
Glorieta	43		508	497		1
Grayburg	3		421	900	2	0
Leonard						6
Lower Clear Fork			30		2	
Lower Leonard				7		
Middle Clear Fork			1		3	
Mississippian	73	3		112	7	
Montoya	15	40	26	68		
Morrow	25	16				
Paddock	135					
Queen	5		106	79	9	3
Rustler	0	10	3	1		
Salado	0	0	6	3		
San Andres	942		2252	4810	167	18
San Angelo					43	
Santa Rosa	6			4		
Seven Rivers			402	8	3	
Simpson Gp.	13	3	14	24		
Spraberry				427		
Strawn Gp.	82	7	3	237	847	47
Tansill			13			
Toborg			110			
Tubb	1		41		3	
Upper Clear Fork			24		1	
Upper Penn	77	297				
Wolfcamp	200	234	107	241	13	
Woodford	3		0	0		
Yates	1		1345	55	2	5
Yeso	21					

Cumulative Disposal Volume



Abbreviation: Gp. = Group.

Table 2. Cumulative Volume (1978–2016) Disposed into Permian Stratigraphic Horizons (Eastern Shelf Pennsylvanian Members are Simplified into Cisco, Canyon, and Strawn Groups)

Injection Stratigraphy	Eastern Shelf
Breckenridge	4
Bunger	22
Caddo	16
Canyon Undifferentiated	369
Capps	11
Cisco Undifferentiated	292
Coleman Junction	25
Cook	3
Dothan	4
Flippen	16
Fry	5
Gardner	5
Goen	69
Gray	0
Gunsight	14
Harkey	0
Home Creek	2
Hope	21
Jennings	2
King	15
Noodle Creek	10
Odom	6
Palo Pinto	98
Saddle Creek	1
Sedwick	1
Strawn Undifferentiated	732
Swastika	45
Tannehill	34

Cumulative Disposal Volume

25 50 75 100 125 150 175 200 225 250 275 300 325 (MMbbls)

4 8 12 16 20 24 28 32 36 40 44 48 52 (trillion L)

specific Pennsylvanian members. The Eastern Shelf stratigraphic members and their SWD volumes (1978–2016) are shown (Figure 5; Table 2) as an expansion of the larger stratigraphic column (Figure 4; Table 1).

CONCLUSIONS

From 1978–2016, 30 billion bbl (~5 trillion L) were disposed into 73 stratigraphic horizons of the Permian Basin via 8201 SWD wells. The highest volumes of cumulative SWD lie near basin margins because of the historical disposal of water coproduced from conventional reservoirs. More recent production from unconventional reservoirs in the basin centers has resulted in a shift of high disposal volumes into the Delaware and Midland Basin centers since 2010. The Northwestern Shelf shows decreasing volumes south to north, and the Eastern Shelf shows decreasing volumes west to east, reflecting a decrease in production activity away from the nucleus of activity in the Permian Basin. The Val Verde Basin has experienced the lowest disposal activity because of the general lack of production in the Val Verde.

Stratigraphically, the Guadalupian-aged Delaware Mountain and Artesia Groups are the highest-volume targets across the Permian Basin. Historically, the Guadalupian has proven to be a low-cost, readily accessible target accepting high water volumes. More recently, disposal into the San Andres Formation in the Midland Basin has resulted in overpressuring and interference with producing wells. Since 2010, New Mexico stopped new permitting into areas with active Guadalupian production to prevent interference.

Operators in Texas are exploring the deep Ellenburger as a target for disposal because of its high intake capacity. However, disposal into the Ellenburger raises concerns about induced seismicity along near-basement faults, as seen in Oklahoma and northcentral Texas. From 2015, New Mexico stopped new permitting into the Ellenburger. New Mexico now preferentially permits disposal into the Devonian and Silurian (Fusselman) Formations; Texas has no analogous stratigraphic preference.

This study characterized the temporal evolution of SWD in terms of geographic and stratigraphic variability in response to potential induced seismicity and regulatory changes within the Permian Basin of Texas and New Mexico. The stratigraphic and spatiotemporal distribution of SWD serves as a critical input into resource utilization and induced seismicity assessments. The primary implications of the stratigraphic and spatiotemporal distribution of SWD from this study are the considerations of disposal capacity and induced seismicity assessments. Disposal capacity may be evaluated by combining stratigraphy and volumes from this study with geologic models of porosity and permeability, hydrogeologic models of pore pressure evolution, and assessment of potentially problematic faults. Results of this study, coupled with TexNet earthquake

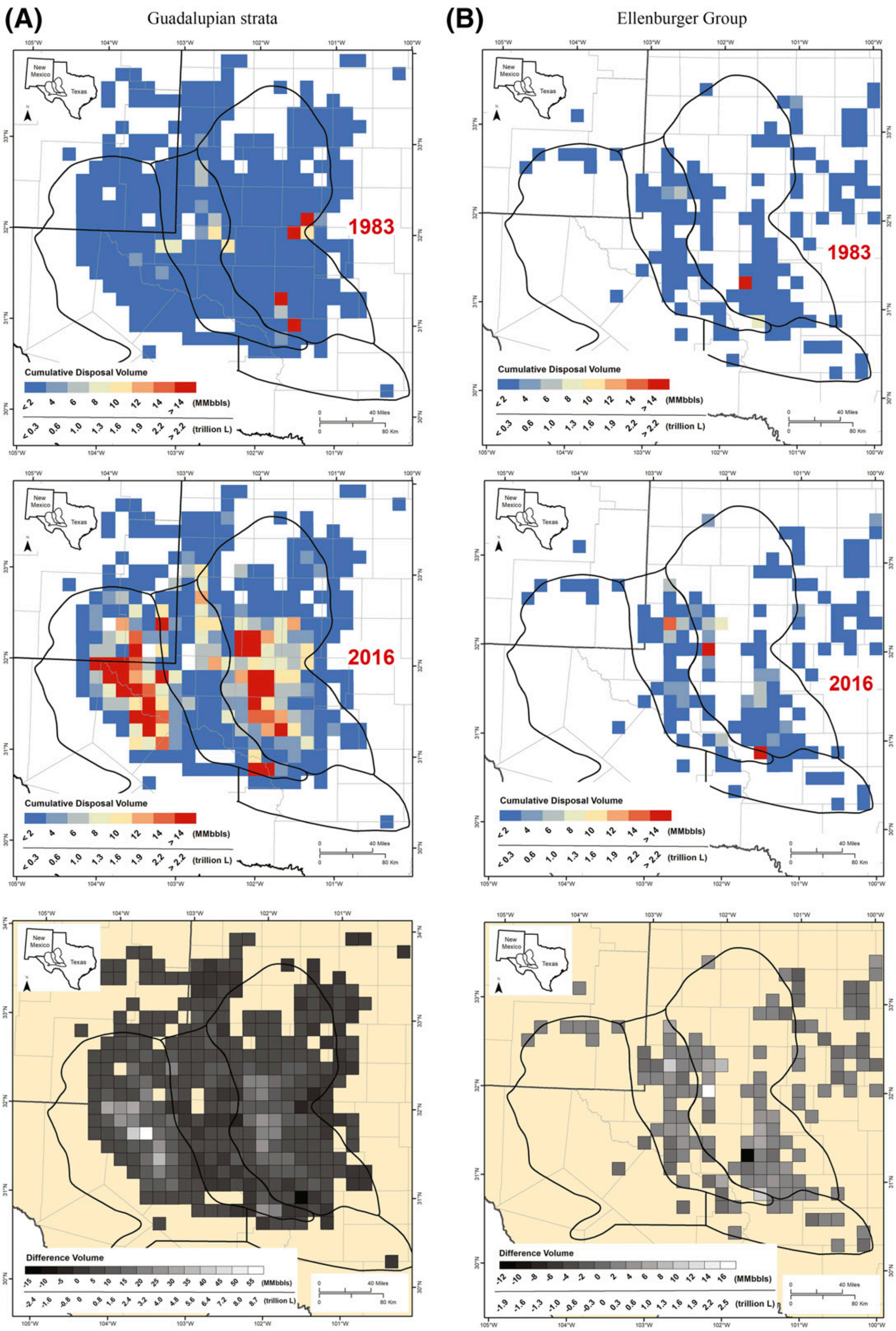


Figure 7. (A) Annual disposal volumes (million barrels) into Guadalupian strata and (B) the Ellenburger Group in 1983 and 2016. A difference map shows the difference between 1983 and 2016 salt-water disposal volumes. Black squares indicate the lowest change from 1983–2016, and white squares indicate the highest change. The greatest increase in Guadalupian-aged formations is in Pecos County, shown highlighted in white (A, bottom). The greatest increase in disposal into the Ellenburger Group is in the Midland Basin, highlighted in white (B, bottom).

data, can provide invaluable information for regional assessments of the opportunities and hazards associated with SWD.

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