Meadows Report 24-001

Revisiting Gunnar Brune's "Major and Historical Springs of Texas"

with an Analysis on the Fractal Character of Springflow

Historical postcard of Rice Springs in Haskell, Texas, circa 1907. From the personal collection of Robert Mace.

Authors:

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The Meadows Center for Water and the Environment, Texas State University

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MEMBER THE TEXAS STATE UNIVERSITY SYSTEM

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Executive Summary

In 1975, nearly 50 years ago, Gunnar Brune published a report at the Texas Water Development Board titled “Major and Historical Springs of Texas.” In this report, he quantified the number of springs that had gone dry by that time. To our knowledge, no one has revisited that study to determine the current status of those springs. When Brune did his study, groundwater users had produced about 250 million acre-feet of water from the state’s aquifers. Today, about 700 million acre-feet of water—nearly three times as much—has been produced, thus leading to our hypothesis that more springs have gone dry since Brune published his 1975 report. To test this hypothesis, we evaluated the current status of springs in his report.

We located springs in the report through a combination of Brune’s approximate latitude-longitude coordinates, descriptions in his report and book; T*he Springs of Texas, Volume 1*, published in 1981; current and historical U.S. Geological Survey topographic sheets, Google Maps and Google Earth Pro, the Texas Water Development Board’s Groundwater Data Viewer and, for difficult-to-locate springs, other external sources, including historical reports and maps, the Texas Springs Facebook Group, and site visits. We then assessed flow status through Google Earth Pro, the Texas Water Development Board’s Groundwater Database Viewer, the Texas Springs Facebook Group, and site visits.

We identified discrepancies in the flow status of springs between the 1975 report and the 1981 book. After correcting the flow status of springs in the 1975 report with those in Brune’s 1981 book, we found that 14 percent of springs had gone dry by 1981 with 23 percent of springs dry today, an increase of 64 percent. Because Brune’s book did not include the entire state and we found the book’s information more reliable, we refined our analysis to include only those springs shared between the report and the book. This refined analysis showed that 11 percent of springs had gone dry by 1981 compared to 30 percent today, an increase of 173 percent, or 2.7 times more.

We also found that springflow volumes follow a power-law—or fractal—distribution with a fractal dimension of 0.72. Using the fractal relationship and correcting for a physical upper limit, we estimated total springflow in the state at 2.1 million acre-feet per year. This compares to Brune’s speculation that total statewide springflow probably amounted to about 3 million acre-feet per year and to a range of estimates of groundwater discharge to surface water in the state from 1.3 million to 9.3 million acre-feet per year.

Introduction

A spring is a natural discharge of groundwater at the land surface (Poehls and Smith 2009[1]). Before human-forced groundwater production, springs over a range of sizes were the primary discharge points for aquifers. Springs can be large or small and represent gravity drainage from an aquifer or artesian flows from a pressurized aquifer. Springs can be ephemeral or continuous with relatively constant or highly variable flows.

Major springs are and were sources of water for flora and fauna and, later, for indigenous peoples, some of which redirected flows for agriculture and domestic uses such as the Jumano and Mescalero (Brune 1952). Early settlers in Texas sometimes named their towns after the local springs, such as Big Spring, Carrizo Springs, Cat Spring, Dripping Springs, and Sulphur Springs. Other towns were located, in part, due to a local spring, such as Austin, Brackettville, Del Rio, Lubbock, San Antonio, and Waco. As technology improved, so did methods of capturing the energy of springflows or the flows themselves and directing them to meet human needs, such as through waterwheels and canals.

As the population grew, so did the production of groundwater in Texas and across the world. The great leap forward in groundwater production occurred during the 1950s when technology and affordability converged to create a nearly 10-fold increase in groundwater pumping across Texas, an increase—fed almost entirely by agricultural use—that remains today (Figure 1).

Besides systematically lowering water levels in many of the state's aquifers (Figure 2), groundwater production also lowered the flows to—and, in some cases, stopped flows to—springs across the state (for example, see Brune 1975, 1981; Mace and others 2020; Mace 2021). Therefore, springs also serve as sentinels for aquifer health, integrating a contributing area of flow for assessing water quality and serving as an important indicator of sustainable production.

While employed with the Texas Water Development Board, Gunnar Brune (born 1914, died 1995) published his report *Major and Historical Springs of Texas* in 1975, where he surveyed the more important springs across the state and their flow status as late as the early 1970s (Brune 1975). This report and his subsequent self-published book, *Springs of Texas, Volume 1* (Brune 1981), remain the definitive works on the springs of Texas. Sadly, Brune did not prepare Volume 2 of his book.

Helen Besse, through Texas A&M University Press, republished Brune's book in 2002, leaving his original text untouched but adding a preface that revisited Brune's overarching themes (Brune and Besse 2002). Heitmuller and Reece (2003) published a database of historically documented springs and spring-flow measurements in Texas using digital and hard-copy data from the U.S. Geological Survey, Texas Water Development Board, and Capitol Environmental Services with additional support from Texas Parks and Wildlife Department for Version 1.2. Heitmuller and Reece (2003) included information on 1,891 springs with 6,924 flow measurements. Helen Besse began reconnaissance work for a Volume 2 of Brune's book (ERF 2006) but abandoned

1 We added the word "natural" to this definition. Poehls and Smith (2009) noted that "The observation of flowing water usually differentiates a spring from a seep, which may simply be a moist area."

the effort after landowners denied access to their property due to the drought and fears that the state would take away their water rights (Helen Besse, personal communication, 2021).

Brune (1975) identified 281 major and historically significant springs. He defined major springs as those with flows greater than or equal to 1 cubic foot per second. Many of the major springs are historically significant, but Brune also included historically notable springs with flows of less than 1 cubic foot per second. Brune did not include any springs with total dissolved solids greater than 3,000 parts per million. Notably, he found that 63 springs had gone dry, with an additional 2 springs inundated by reservoirs.

While the passage of time generally does not change whether a spring is historical[2] or change whether a spring is major[3], the status of a spring—whether it is still flowing or not—can change since pumping has continued across the state since the 1970s. In fact, groundwater users have produced an additional 500 million acre-feet of groundwater from Texas' aquifers since Brune's study in 1975, twice as much as was produced when Brune did his study (Figure 1).

The purpose of this study was to revisit the 281 springs in Brune's 1975 report to assess their current flow status with the hypothesis that more springs have gone dry since the publication of his report. We evaluated Brune's 1975 report because it (1) was state-wide in scope, (2) included all the known major springs of the state, and (3) was manageable (281 springs versus the more than 2,900 springs in Brune's 1981 book). We used a variety of maps and remote sensing techniques and a few field trips to revisit the springs in Brune's report. Once we completed the dataset, we also investigated the fractal nature of springflows with the hypothesis that springflows follow a power-law relationship.

2 Although what is historical is subject to argument.

3 Although Hunt and others (2013) recently identified a previously unknown major spring (Pleasant Valley Spring) in the bed of the Blanco River near Fischer Store.

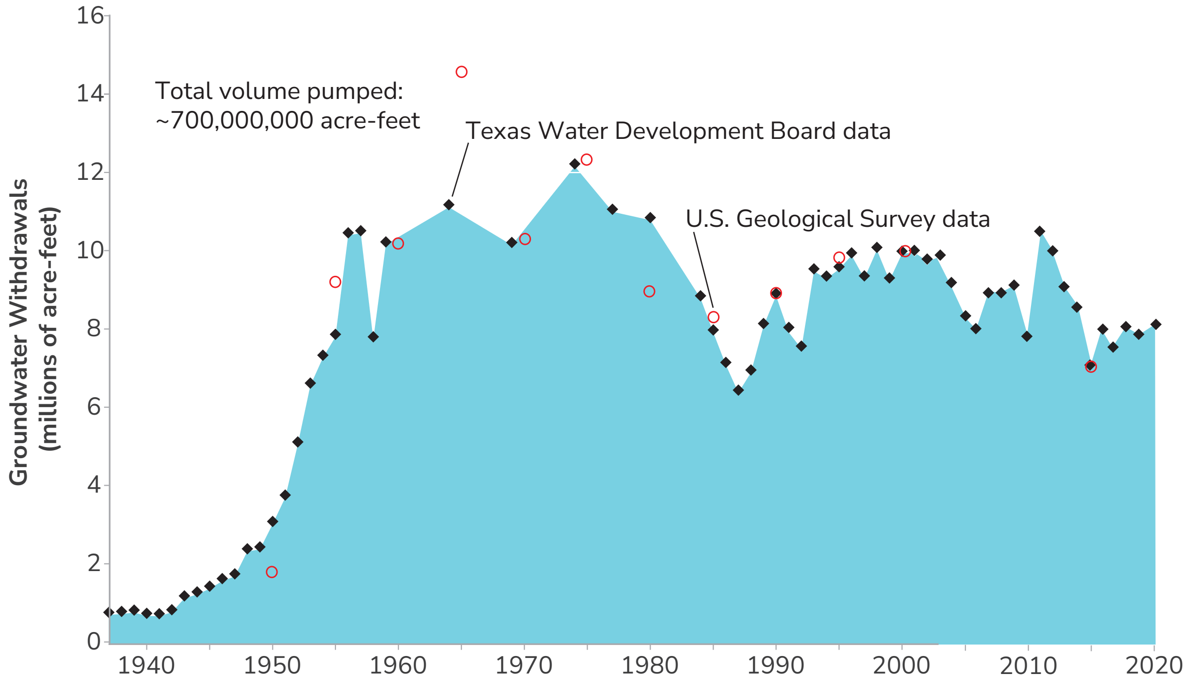

Figure 1. Groundwater use in Texas since 1937 (after Mace [2021]).

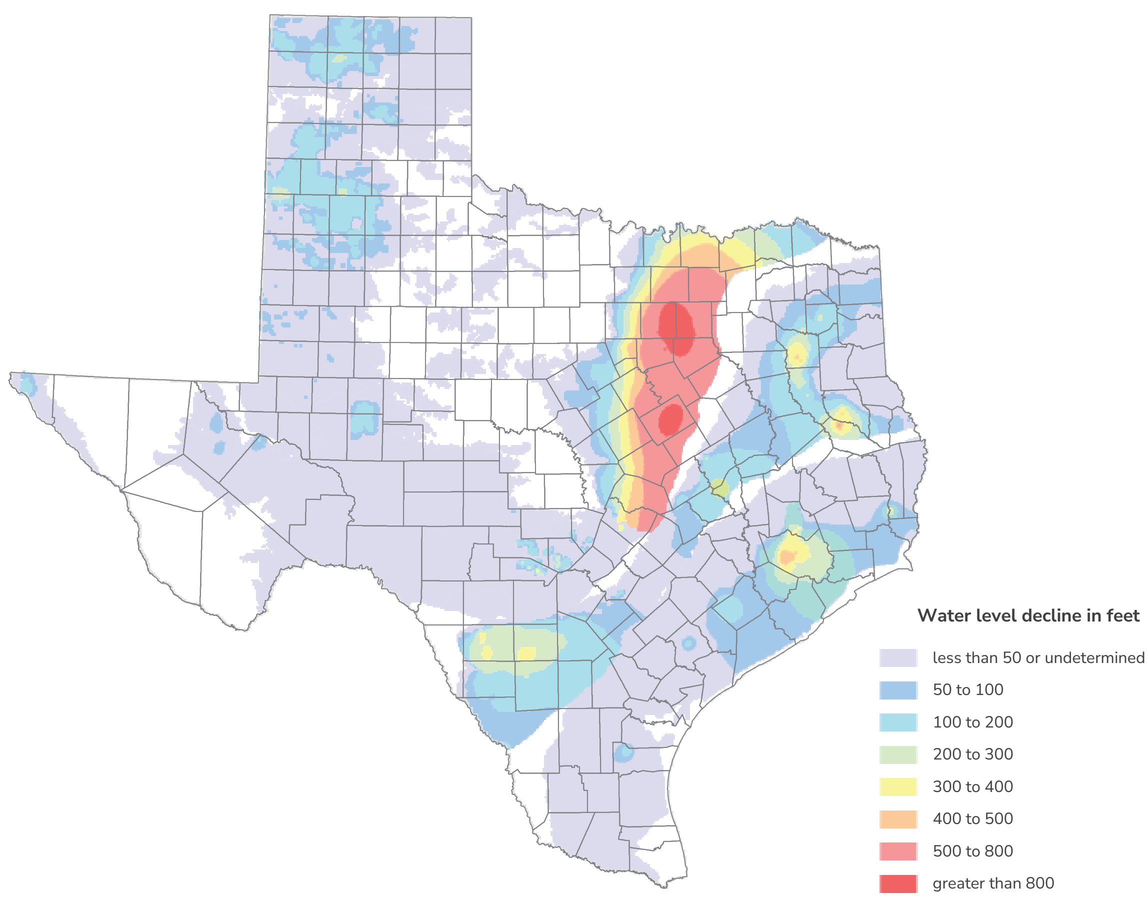

Figure 2. Declines in hydraulic heads (water levels) in the major aquifers of Texas from pre-development to ~2000 (from TWDB 2012).

Database Development and Evaluation of Spring Status

To assess the status of springs today compared to the early 1970s, we (1) entered information from the Brune (1975) report into an Excel spreadsheet; (2) located the springs through a combination of Brune's approximate latitude-longitude coordinates, his descriptions in Brune (1975) and Brune (1981), U.S. Geological Survey topographic sheets, Google Maps and Google Earth Pro, the Texas Water Development Board's Groundwater Data Viewer and, for difficult-to-locate springs, other external sources, including historical reports and maps, the Texas Springs Facebook Group, and site visits; and (3) assessed flow status through Google Earth Pro, the Texas Water Development Board's Groundwater Database Viewer, the Texas Springs Facebook Group, and site visits. After completing the database, we then attempted to recreate the numbers Brune reported in his 1975 report. After that, we evaluated the current status of the springs to update the number of springs that have gone dry.

We first created a database of spring information from Brune (1975), including Brune's identification number, spring name, county, latitude-longitude (reported in degrees and minutes), and rate and date of the maximum reported springflow and last recorded springflow. Based on the last recorded springflow information from Brune's report, we then assigned a springflow status (FLOWING, DRY, INUNDATED, UNKNOWN) to each spring (in some cases, Brune did not provide information on the flow status of the spring, hence UNKNOWN). During our efforts to locate springs, we noticed some discrepancies between his 1975 report and his 1981 book on flow status, so we also, where available, entered the springflow status from his book.

Once we entered the Brune (1975) information, we calculated latitude and longitude in decimal degrees and began searching for the spring using current and historical U.S. Geological Survey topographic maps through the Historical Topographic Map Explorer (USGS 2021). Because Brune (1975) only reported locations to the nearest minute (which amounts to about +/- 6,000 feet), we needed to search a relatively broad area (about four square miles) to locate a spring. We first checked to see if the topographic sheets identified the spring by name and, if not, located any identified but unnamed springs in the area. If the U.S. Geological Survey had not identified any springs in the area, we used the topographic sheets to identify perennial flow in any nearby creeks.

If we located a spring or, in some cases, multiple springs, we corroborated that location with Brune's descriptions in his report and book. The book has richer details about the springs and was helpful in locating springs or confirming locations. We also checked the Texas Water Development Board's Groundwater Data Viewer (TWDB 2022) for location information from scans of the original survey sheets; however, we found that many locations in the Board's database were based on Heitmuller and Reece (2003) and that those locations were often not correct (in Heitmuller and Reece's defense, their project was focused on compiling existing spring information, not confirming the accuracy of that information). ERF (2006) noted that much of the location data for springs in the Texas Water Development Board's database were also inaccurate due to methods used to calculate latitude-longitudes before the advent of global positioning systems and remote imagery.

To confirm spring locations, we used Google Earth Pro as well as the last zoom of the imagery basemap in the Groundwater Data Viewer (which was at a higher resolution than Google Earth Pro)[4]. Google Earth Pro tended to have half a dozen or more dates with imagery with enough resolution—generally since 2006 —to identify springs and springflow conditions. The number of imagery dates and the time range generally allowed for imagery that included winter months when deciduous trees had lost their leaves, thus allowing for better inspection for and of springs, and to include the second worst state-wide drought of record (2011 to 2015), which allowed perennially flowing springs to be more easily identified through foliage.

Often, a location included several or more springs. Headwaters of streams and rivers often include several springs downstream of the headspring as the aquifer intersects the streambed. In some cases, the headspring described by Brune would be dry, but a short distance downstream, it was clear there were springs that were still flowing. In these cases, we assigned the location to the uppermost springs and described the springs as flowing.

For each location, we assigned a confidence level expressed as a probability between zero (no confidence) and 1 (high confidence). Both of us entered data into the database as we located springs, but the lead author reviewed all locations and assigned final confidence numbers to ensure as much consistency as possible across the full suite of springs. Although we made our best efforts to accurately locate springs, we are confident that we have made errors or incorrect assumptions. Accordingly, we encourage readers to check our results and contact us when they find a mistake. We will maintain an updated version of the data on the website for The Meadows Center for Water and the Environment (www.meadowscenter.txst.edu) in addition to the original data.

In our spreadsheet, we noted if a spring was named on a topographic map, if a spring was noted but not named, the name of the most recent topographic map with the spring identified on it, and any notes on locating the spring. Sometimes, when the topographic maps did not include a spring location but showed where a stream was perennial, we used the upstream end of the perennial flow as the spring location. In some cases, failed springs (springs that went dry or were inundated by reservoirs) were removed from later topographic maps. Therefore, we used the Historical Topographic Map Explorer (USGS 2021) to inspect historical maps for evidence of springs. If we used a topographic map to identify a spring, we indicated which topographic sheet we used, generally the most recent sheet that showed the spring.

Google Maps has locations for many of the springs in Brune (1975); however, many were incorrect. We realized later that many, if not all, of these locations came from U.S. Geological Survey databases that include information from Heitmuller and Reece (2003). Therefore, we noted on our spreadsheet if Google Maps showed a spring's location and if the location was accurate compared to our analysis. We also used Google Maps to assign a latitude-longitude to confirmed spring locations.

Based on imagery from Google Earth Pro and the Groundwater Data Viewer, we then attempted to assess whether or not a spring was still flowing. In many cases, we could confirm springflow by visually confirming the presence of water in Google Earth Pro

4 Imagery for the last zoom is from the Texas Imagery Service, which updates the imagery every two years.

or the Groundwater Data Viewer (Figure 3 shows an example of resolution in Google Earth, and Figure 4 shows the resolution in the Board's Groundwater Data Viewer). We also assigned a confidence level expressed as a probability between zero and 1 for flow status. If we could see water, we assigned a confidence of 1. If we could see what appeared to be spring-derived greenery, we assigned a confidence of 0.7. If we could not determine flow status, we assigned a confidence of zero. Depending on what we could or could not see, we assigned a gradation of confidence. As with location, the lead author assigned the final confidence on spring status to have an analysis that was as consistent as possible.

Like Brune (1975), we then assigned a spring status (FLOWING, DRY, INUNDATED, UNKNOWN) based on our analysis. With Google Earth Pro and a half-dozen to a dozen and more images of a site, we could determine if a spring was perennial or intermittent, so we added a new category (INTERMITTENT) to reflect the less-than-perennial reliability of recent (over the past ~15 years) springflows.

Once we completed the database, we made one more pass through each spring to verify location and status information and to add information on spring access (public, private, private near public access [in other words, viewable from a road or navigable waterway]), an associated Texas Water Development Board well number (if available), and whether or not the Texas Water Development Board location was accurate.

For any spring with a location confidence of less than 1, we researched the spring more deeply to attempt to refine its location. We did this by reviewing Brune's sources and other sources, including hydrogeologic reports by the state and the U.S. Geological Survey, historic maps generally available through the General Land Office's web page, other historical documents, and the literature. We also posted to the Texas Springs Group on Facebook, which includes professionals and cave and spring enthusiasts, seeking location and spring status information and confirmation. If publicly accessible with uncertainty in location and flow status, we attempted to visit the spring to confirm location and status. For the remaining springs, we contacted groundwater conservation districts, if one existed, and landowners before completing the database.

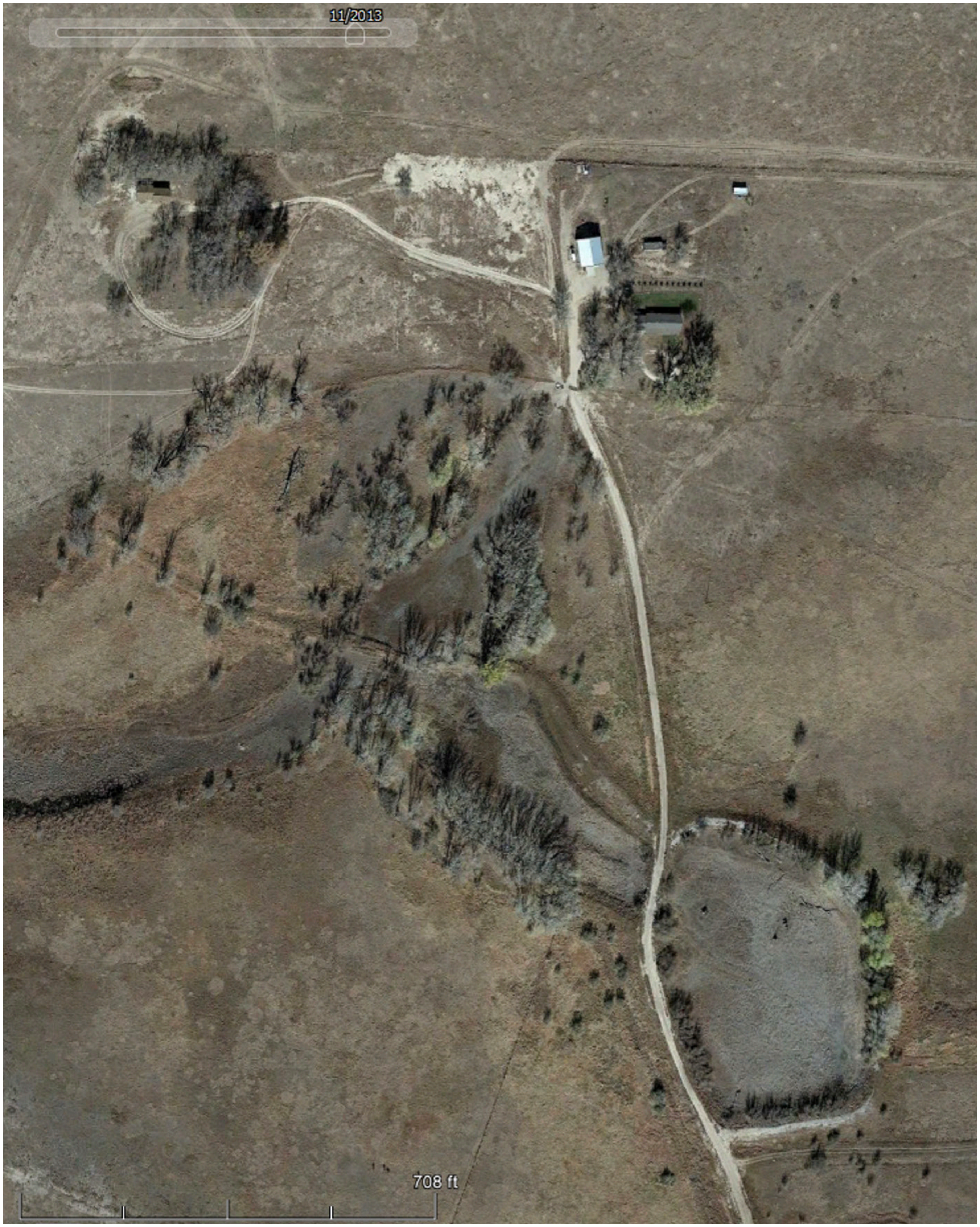

Figure 3. Buffalo Springs in Dallam County in November 2012 using Google Earth Pro (north is to the top of the image). Based on this imagery (and others), we marked this spring as having gone dry.

Figure 4. Ebeling Springs in Burnet County of unknown vintage (but relatively recent) using the Texas Water Development Board's Groundwater Data Viewer (north is to the top of the image). Based on this imagery (and others), we marked these springs as flowing.

Spring Analysis

Our analysis consisted of three primary activities: (1) confirming Brune's numbers with our database, (2) comparing our recent assessment of flow status to the Brune (1975) report, and (3) comparing the flow status of springs between his 1975 report and 1981 book.

Confirming spring numbers in Brune (1975)

Confirming Brune's numbers in his 1975 report ensured we understood how he counted springs and spring status. Brune (1975) noted that his report included information on 281 springs; we counted 281 springs by (1) dropping Leona Springs Groups 1-3 (to avoid a double count since Group 1, Group 2, and Group 3 were all included in Group 4) and (2) including Hynson, Marshall, Noonday Camp, and Iron springs (all one entry) in the tally although Brune (1975), for an unknown reason, did not assign them a spring number.

Of the 281 springs listed in Brune (1975), we located 140 springs based on topographic sheets (69 were named on the sheets, 67 were indicated as springs but not named, and 4 were located on other information on the sheets, such as headwaters of a stream, a named feature [such as spring lake], or the location of a landmark). Locations for 23 of the springs were based on descriptions in Brune (1975) and/or Brune (1981), 20 were based on Google Earth Pro, and 20 were based on information from the Texas Water Development Board's Groundwater Data Viewer. Locations for 68 springs required additional research, including historical source documents, comparing stream traces to the Camino Real, and other sources. We conducted site visits for 10 of the springs to accurately locate them. We assigned a probability of 1.0 in our confidence of location to 249 springs, 0.9 to 27 springs, 0.8 to 3 springs, and 0.7 to 2 springs.

Brune (1975) described 63 springs as having gone dry and 2 springs inundated by reservoirs. Based on his descriptions, we found 63 dry springs and 5 inundated. Although Brune (1975) did not report flow status beyond dry and inundated in his summary, we also tallied how many he described as flowing (191), intermittent (7), and unknown (15; Figure 5). Therefore, of the springs that were flowing, intermittent, and inundated (assuming that the inundated springs were still flowing at the time of his report), 24.1 percent of the springs in his report with reported flow status had gone dry by ~1973 (the most recent springflow measurements in his report were made in 1973).

More springs may have gone dry by the time Brune published his report in 1975. This is because he and Texas Water Development Board technicians were not able to visit each spring in his report, so some of the most recent springflow measurements were dated for his study. Of the 194 springs that Brune (1975) reported as flowing or intermittent at their most recent measurement date, 3 measurements were made in the 1800s, 1 in the 1910s, 1 in the 1920s, 7 in the 1930s, 9 in the 1940s, 19 in the 1950s, 58 in the 1960s, and 96 in the 1970s (Figure 5). Of the 61 springs that Brune (1975) reported as dry at their most recent measurement date, 1 measurement was made in the 1920s, 2 in the 1930s, 4 in the 1940s, 3 in the 1950s, 25 in the 1960s, and 26 in the 1970s (Figure 5).

Comparing springflow status from Brune (1975) to today

For this section, we first present a full summary of our analysis, including the flow status on the 15 springs Brune (1975) did not report on. After that, to directly compare our numbers to Brune's, we then removed the 15 springs Brune did not report on from our analysis dataset. We conclude with a discussion of these results. Since we assigned a probability on the accuracy of our flow assessments, we present our results with two numbers: the first is our best whole number estimate of springflow status, and the second (inside parentheses) is the risked estimate reflecting the assigned certainty. In other words, if we assessed a 90 percent certainty that a spring was flowing, that spring counted as 0.9 springs.

We assessed the flow status of all 281 springs included in Brune (1975). We found 194 (192.1) springs flowing, 11 (10.9) intermittent, 66 (63.8) dry, and 10 (10) inundated (Figure 6). Therefore, based on this analysis, 23.5 (23.0) percent of the major and historical springs have gone dry since Brune's analysis was published in 1975.

To compare our springflow analysis directly with Brune's (1975) analysis, we removed the 15 springs with no reported flow status in his report and recounted the springs. This resulted in 189 (187.3) springs flowing, 11 (10.9) intermittent, 57 (55) dry, and 9 (9) inundated.

Interestingly, we found fewer failed springs than Brune (1975) did: 57 (56) compared to Brune's 63. A closer inspection between Brune's status and our update revealed that 71 springs changed flow status between Brune (1975) and our update, including 1 spring changing from dry to inundated, 2 from dry to intermittent, 28 from dry to flowing, 4 from intermittent to flowing, 7 from flowing to intermittent, 1 from intermittent to dry, 25 from flowing to dry, and 3 from flowing to inundated.

There are several possible explanations for this decrease in the number of dry springs. One is how Brune (1975) determined flow status in his report, namely that a spring was considered flowing or dry based on the most recent measurement. However, some springs are naturally intermittent (in other words, they were intermittent before humans began producing groundwater), while others are intermittent due to seasonal production or the dynamics of that production in concert with the weather or other factors. So, one explanation may be that we evaluated springs during a wetter period and were, therefore, more likely to flow. For example, the lead author's 1,000-mile journey through East Texas in 2021 to visit springs was amidst one of the wetter Julys on record. We also evaluated springflow status over a longer period—about 15 years—and, following Brune's lead, considered intermittent springs as flowing for the sake of the analysis.

Another explanation is that groundwater production declined, thus raising water levels and restoring flows to some springs. Statewide, at least, this may be a possibility since groundwater production peaked in the 1970s and has been somewhat lower since. However, groundwater production has continued to lower water levels in aquifers across the state, which would suggest that spring flows should be lower, not higher, if this continued production was not in equilibrium with the aquifer.

Another possibility is that there were errors in the measurements used or the analysis done by Brune (1975). While assessing spring locations, we used Brune's 1975 report, but we also used his 1981 book, which included richer descriptions of the springs that clearly reflected a post-1975 visit. We noticed during this task that springflow status in the report didn't always agree with the status in the book.

Comparing springs in Brune (1975) to Brune (1981)

Because of the difference in springflow status between the report and the book, we went through the book and recorded springflow status for the springs listed in the report. Unfortunately, as previously mentioned, Brune's book does not cover the entire state. Of the 281 springs in Brune (1975), 180 springs were also included in Brune (1981). Of the 180 springs shared between the report and the book, 170 had flow status defined in the report. Of these, 42 springs (24.3 percent) had a different flow status in the book as compared to the report. A total of 30 springs "changed" from dry to flowing, 3 from flowing to dry, 6 from intermittent to flowing, 1 from flowing to inundated, and 2 from inundated to flowing.

A total of 30 springs going from dry to flowing seems quite high over a short period. After taking a closer look at the springs that changed flow status between the report and the book, we found that (1) 25 of the springs that were deemed dry by Brune (1975) probably should have been deemed intermittent based on site visits in the late 1970s, (2) 5 of the springs appeared to have been erroneously marked as dry based on Brune (1981) removing dry measurements and finding them flowing in the late 1970s (it's unclear where the dry measurements in Brune [1975] came from), (3) 3 of the springs should have been marked dry due to additional information, (4) 1 spring that went from flowing to inundated between 1975 and 1981 is accurate, and (5) 2 wells that went from inundated to flowing should have been inundated in the book (it appears Brune [1981] decided to assign 'flowing' to an inundated spring if there was evidence of flow at the springs; however, there isn't flow information at all the inundated springs, so we decided that inundated means inundated). One additional spring went from unknown status to dry with additional information that the spring had gone dry in the 1930s.

In Brune (1981), it's clear which springs he visited in person since he included rich descriptions of the flora and fauna, the landowners, and the springs themselves. Therefore, we concluded that the spring statuses in Brune (1981) were more accurate than those in Brune (1975).

Comparing spring status in Brune (1975), as modified by Brune (1981), to today

Using the Brune (1975) data as modified by springflow status from Brune (1981) and then removing the remaining springs of unknown flow status results in a total of 275 springs. Of these springs, 231 were flowing, 1 was intermittent, 38 were dry, and 5 were inundated. Our recent assessment for these same springs resulted in 191 (189.1) flowing, 11 (10.9) intermittent, 63 (60.9) dry, and 10 (10) inundated (Figure 7). This suggests that an additional 25 (22.9) springs went dry between the 1975 report and our survey, an increase of 66 (60) percent. That means that, of the springs listed in Brune (1975) with flow status updated by Brune (1981), 23 (22) percent have gone dry as of today, up from 14 percent when Brune published his report and book.

The analysis above includes springs in the report that were not included in the book. Given that 24.3 percent of the springs shared between the report and book differed in flow status suggests that it is likely there are further disagreements that we are unaware of. Therefore, we further modified our analysis to include only the springs, sans the unknowns, that were included in both the report and the book. This resulted in 179 springs from the Brune book, where 153 were flowing, 1 was intermittent, 20 had gone dry, and 5 were inundated. In comparison, our assessment for these same springs showed that 106 (104.5) were flowing, 11 (10.9) were intermittent, 53 (51.5) had gone dry, and 9 (9) were inundated. This suggests that an additional 33 (31.5) springs went dry between the 1975 report and our evaluation, an increase of 165 (158) percent. That means that, of the springs listed in Brune (1975) included in Brune (1981) with flow status updated by Brune (1981), 30 (29) percent have gone dry as of today, up from 11 percent when Brune published his report and book.

A total of 52 springs changed their flow status from the 1975 report to today: 35 went from flowing to dry, 1 went from intermittent to flowing, 10 went from flowing to intermittent, 4 went from flowing to inundated, 1 went from dry to flowing, and 1 went from dry to intermittent.

The spring that went from dry to flowing is XIT Springs. Although the headspring has gone dry, there is evidence of flow downstream where a lower water level in the underlying aquifer appears to intersect with the land surface. We deemed these springs to still be flowing even though the upper reach had gone dry. Brune (1975, 1981) may have assessed these springs as dry because the headspring had ceased to flow at that time. Alternatively, the springs may have returned; however, that seems unlikely given that they issue from the Ogallala, an aquifer with steady production and long-term water-level declines. Comanche Springs went from dry (Brune 1975, 1981) to intermittent. These springs had indeed gone dry by the time Brune wrote his report and book but intermittently returned starting in the mid-1980s and continue to flow intermittently today due to decreased pumping from the aquifer (Mace and others 2020).

In summary, based on the previous two analyses, by the time Brune published his book in 1981, 11 to 14 percent of the major and historical springs he investigated had gone dry. More recently, based on the present study, 23 to 30 percent of the springs have now gone dry, an increase of 64 to 173 percent over the past 50 or so years.

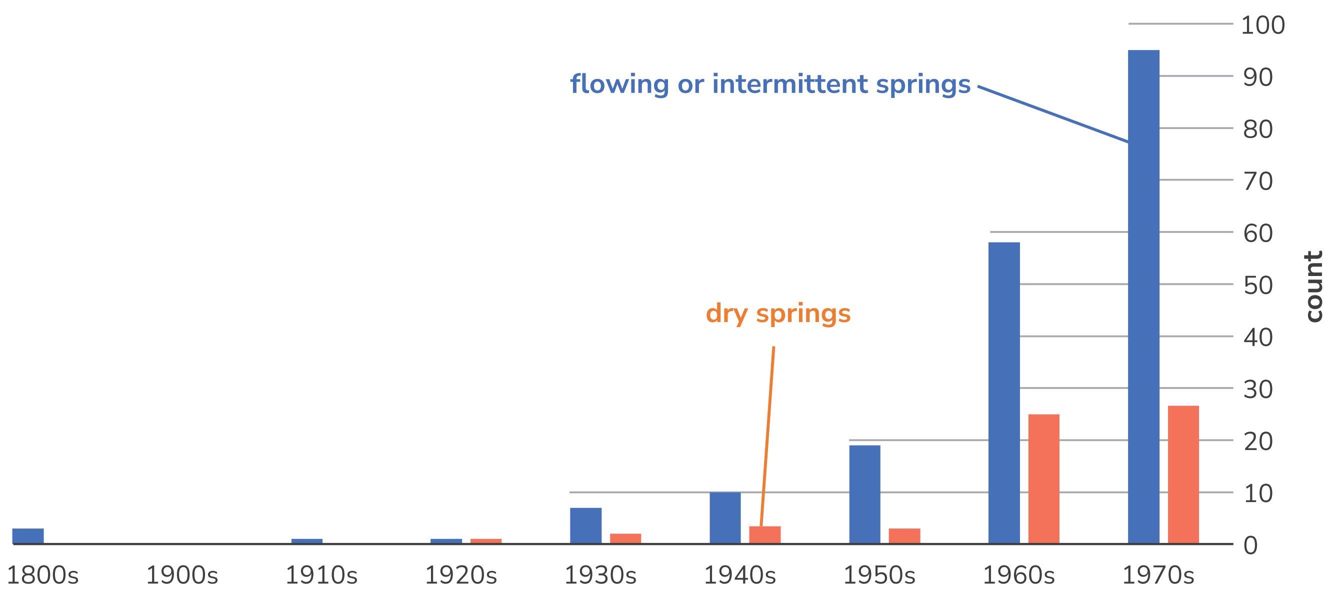

Figure 5. Date of the most recent measurement or springflow report in Brune (1975).

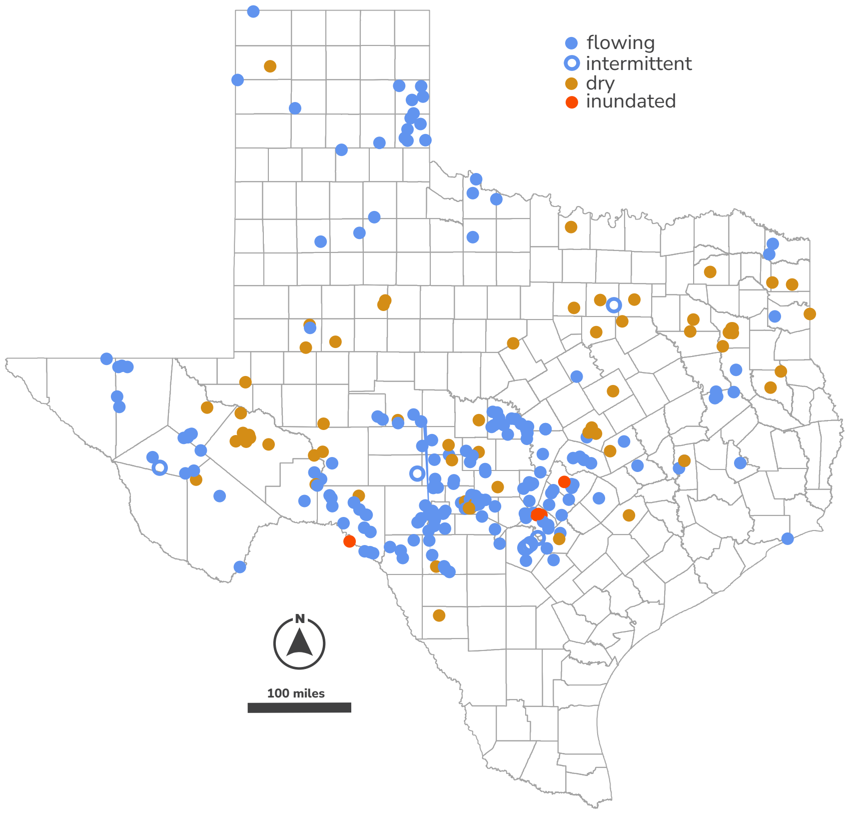

Figure 6. Location and status of springs in Brune (1975). Does not include springs with unknown status.

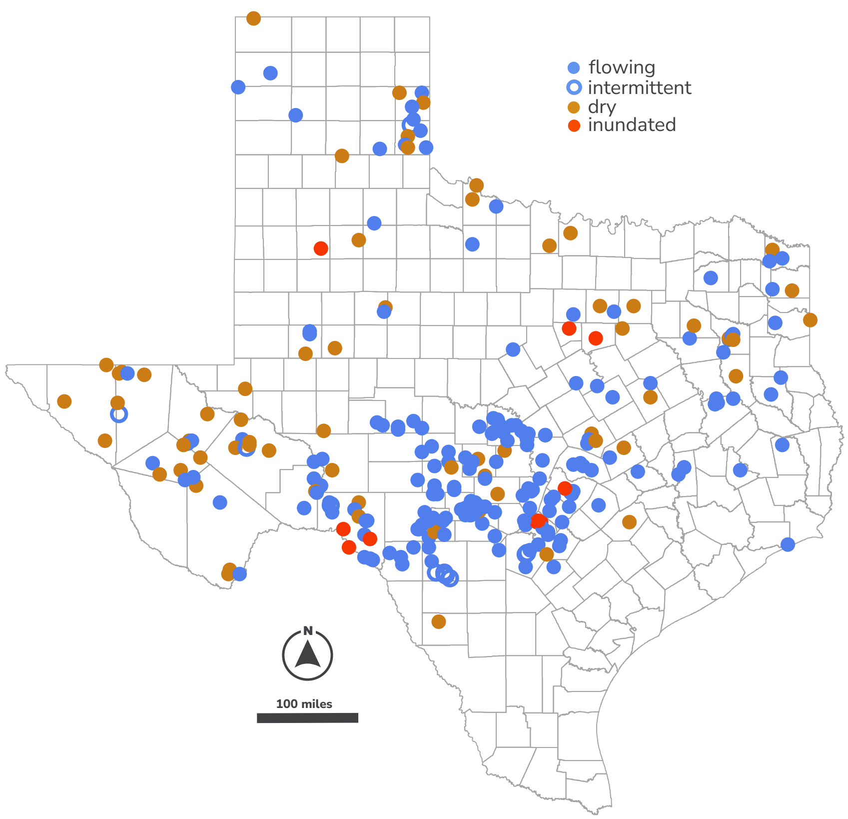

Figure 7. Current status of the springs in Brune (1975). Includes 15 springs Brune (1975) included in his report but did not include flow status.

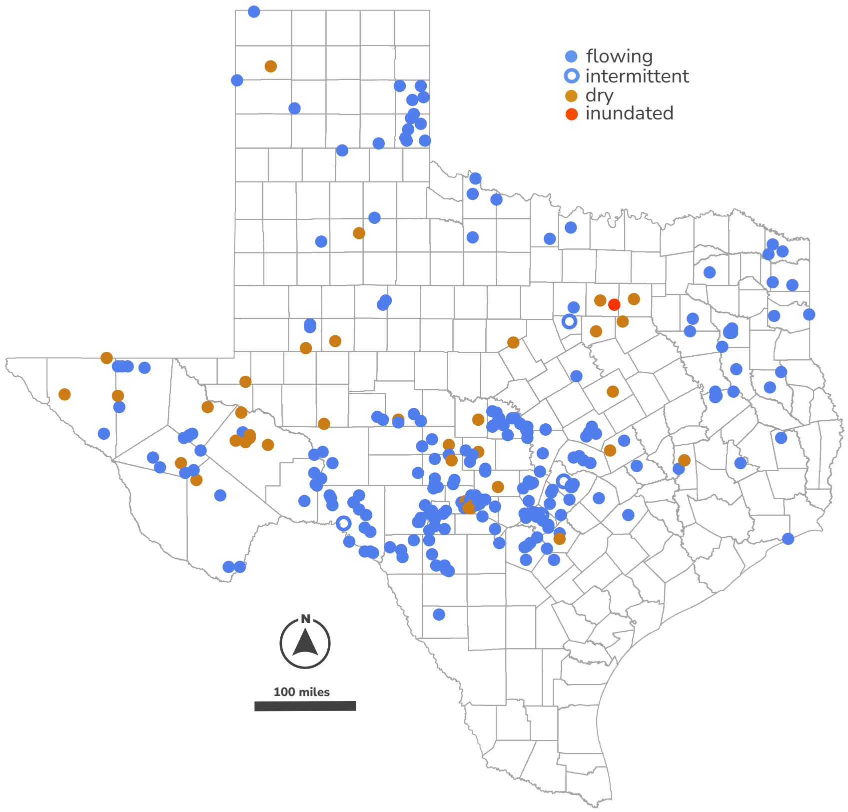

Figure 8. Location and status of springs in Brune (1975) as modified by Brune (1981).

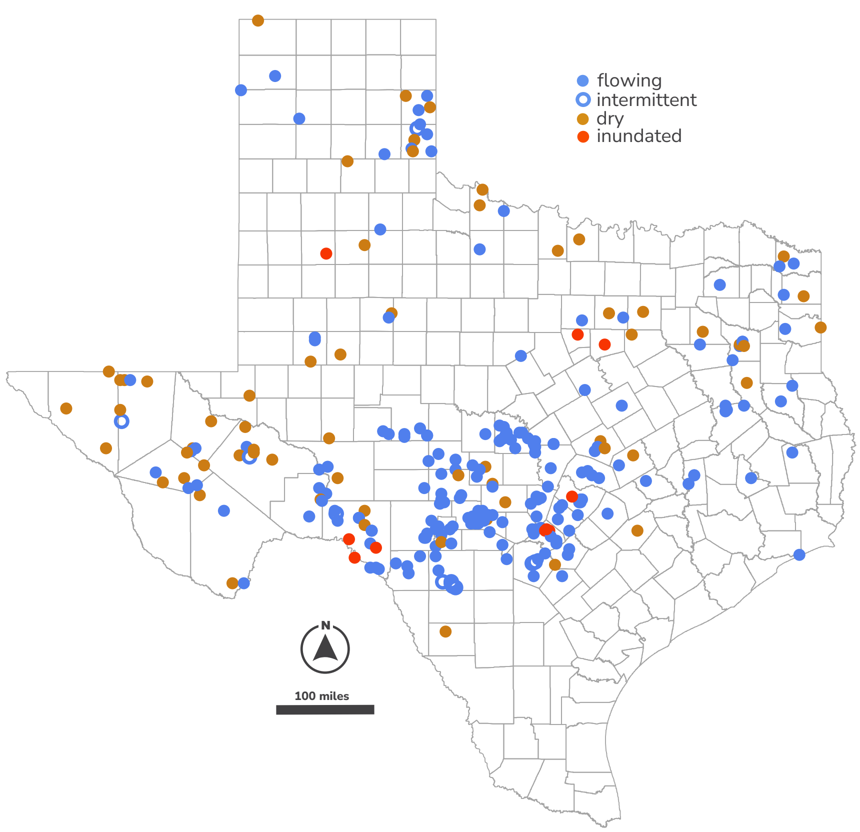

Figure 9. Current status of the springs in Brune (1975) as modified by Brune (1981).

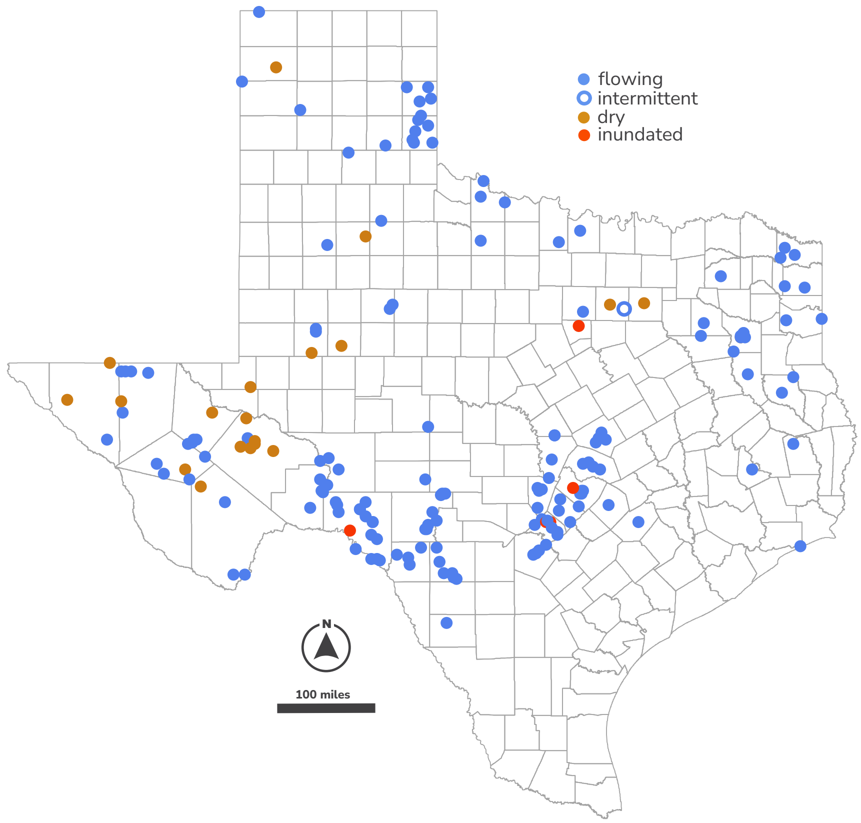

Figure 10. Status of the springs in Brune (1981) included in Brune (1975).

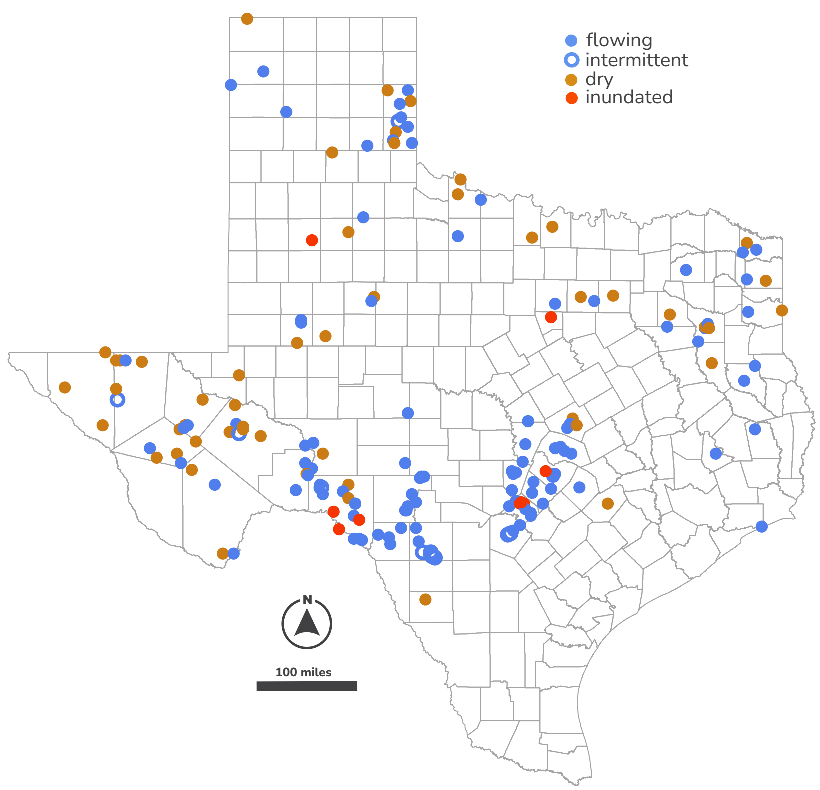

Figure 11. Current status of the springs in Brune (1981) included in Brune (1975).

Fractal Analysis

In the early 2000s, the lead author worked with Dr. Randall Marrett at The University of Texas at Austin to investigate fractal scaling in fracture apertures and the area of dissolution features in outcrops of Edwards rocks in the San Antonio area (Mace and others 2005). Given this experience and the knowledge that flow from many springs is controlled by fractures and/or dissolution features, we hypothesized that springflows would also follow a fractal—power-law—distribution. Given that Brune sought to include all springs greater than 10 cubic feet per second, we also hypothesized that fractal behavior would start to be observed in the data at 1 cubic foot per second.

To assess fractal behavior of springflows, we (1) compiled the highest reported springflows from Brune (1975, 1981) for each spring, (2) converted flows into consistent units (Brune used several units to quantify flow), (3) ranked the springflows from largest to smallest, (4) calculated the logarithms of the ranking and the springflows, and (5) plotted log ranking against log springflow.

Most of the highest reported springflows from Brune (1975, 1981) occurred in the 1960s and the 1930s (Figure 12). Although most of the more recent measurements occurred in the 1970s (Figure 5), none of the highest measurements occurred in the 1970s (Figure 12). Given that there were not consistent measurements made at all springs over time, measurements of the highest springflows aren't necessarily—and almost certainly are not—indicative of the highest historical springflows. At the very least, these measurements provide an approximate magnitude of the flows at these springs.

The linear part of the power-law plot, starting at about 1 cubic-feet per second and extending to the second largest spring (San Marcos Springs) suggests that springflow does, indeed, follow a power law (fractal) distribution (Figure 13).

Measured, natural features do not tend to show fractal behavior over the entire sampling range. This is due to sampling artifacts. Because smaller-sized features are more difficult to measure, truncation artifacts often appear (Barton and Zoback 1992, Marrett 1996, Mace and others 2005). For smaller values, this suggests that not all the smaller features were measured. As previously noted, Brune (1975) did not include all the springs with flows less than 1 cubic feet per second, so we have a confirmed undersampling of springs less than this size. This doesn't mean that the fractal behavior of springflow necessarily extends to smaller springs, but it does mean that the collected data doesn't disallow that extension.

The upper end of collected data may bend downwards due to censoring artifacts where censoring occurs due to the limited size of a study area (Barton and Zoback 1992, Marrett 1996, Mace and others 2005). A study area of limited size may miss some or all of the larger features. In our case, because the entire state is our study area and springs are point locations, we do not have censoring. The lower-than-expected flow at Comal Springs, when compared to the fractal relationship, could be due to groundwater production artificially lowering flow at the springs; however, the x-axis intercept for N = 1 is about 1,000 cubic feet per second—an unlikely flow for the Comal Springs during pre-development times. This suggests a physical- limit artifact on the upper end of our distribution where the geology, hydrology, and meteorology can only produce so much springflow for the largest features (or, in this case, feature).

Total spring flow in Texas

So, what can a fractal relationship tell us about springflow in Texas? If we assume that the fractal nature of springflow continues for springflows less than 1 cubic feet per second, we can use the power-law relationship to estimate (1) the number of springs greater than a certain size for the study area (which in our case is Texas) and (2) the total amount of springflow in the state. To do this, we developed an equation to represent the fractal relationship for spring flow based on a modification of equations for fracture aperture and dissolution feature cross-sectional area (Marrett 1996, Mace and others 2005).

If we fit a line to the linear part of the plot, the equation that describes the line is

$$log(N_i) = D * log(Q_i) + log(\omega) \tag{1}$$

where N_i is the rank number for rank *i*, *D* is the slope of the line (which is also the fractal dimension), *Qi* is the springflow for rank *i*, and *log*(*w*) is the y-intercept for when *log*(Q_i) equals zero. Our relationship results in a slope (fractal dimension), *D*, of 0.72 and an intercept, *log*(*w*), of 2.18, which, after taking the antilog, results in a *w* of 151.

Rearranging the equation and taking the antilog of both sides results in

$$N_i = \omega Q_i^{-D} = \omega \frac{1}{Q_i^D} \tag{2}$$

With this equation, we can calculate the number of springs greater than a certain size. For example, the number of springs that are 0.01 cubic feet per second or larger in Texas is 4,159 (which means the Texas Water Development Board spring survey team has its work cut out for it!).

Solving Equation 2 for Q_i results in

$$Q_i = \left(\frac{\omega}{N_i}\right)^{1/D} \tag{3}$$

which allows for the calculation of springflow for any ranked number spring, *i*.

We can also use fractal scaling to estimate total springflow over a study area, assuming that the fractal relationship applies at all scales. To do this, we used the Riemann zeta function (Apostal 1957) as a general expression of aggregate attributes following fractal scaling (Marrett 1996). The Riemann zeta function, ζ(x), can be approximated by the sum of its first three terms and the first two terms of the Euler-Maclaurin summation formula (Dahlquist and Bjőrck 1974):

$$\zeta(x) \cong 1 + 2^{-x} + 3^{-x} + \frac{x+7}{2(x-1)} 4^{-x} \tag{4}$$

or, alternatively,

$$\zeta(x) \cong 1 + \frac{1}{2^x} + \frac{1}{3^x} + \frac{x+7}{2(x-1)} * \frac{1}{4^x} \tag{5}$$

where x is the argument.

Therefore, the aggregate sum of springflow over a study area is

$$\sum_{i=1}^{\infty} Q_i = \zeta\left(\frac{1}{D}\right) Q_1 \quad (6)$$

where Q_1 is the springflow estimated from the relationship for the biggest spring (i = 1), which is also the x-intercept for the line fit.

Solving Equation (3) for i = 1 results in

$$\sum_{i=1}^{\infty} Q_i = \zeta\left(\frac{1}{D}\right) (\omega)^{1/D} \quad (7)$$

Solving this equation for our relationship results in total state-wide springflow of 3,370 cubic feet per second. Because (1) the relationship predicts a springflow at the largest spring, Comal Springs, of 1,063 cubic feet per second; (2) we do not have a censoring artifact; and (3) the flow estimated at Comal Springs with this relationship is unrealistically high, we reduced the total state-wide flow by the difference between that flow and the highest measured flow at Comal Springs (534 cubic feet per second), resulting in a final state-wide springflow of 2,841 cubic feet per second.

It might seem ambitious to use this analysis to estimate total springflow and natural groundwater discharge, so let's compare our fractal estimate (which amounts to 2.06 million acre-feet per year) to other published estimates. Brune (1975) reported that the total springflow in his analysis amounted to 1.15 million acre-feet. Our analysis for the same set of springs, using the highest reported flows, amounts to 1.52 million acre-feet. Brune (1975) speculated that total springflow probably amounted to about 3 million acre-feet per year. We are not aware of any other estimates of statewide springflows.

What exactly is a spring? Kresic (2009) stated that, "In general, a spring is any location at the land surface where groundwater discharges from an aquifer, creating a visible flow." Tolman (1937), Todd (1959), and Porges and Hammer (2001) require "concentrated discharge" and "a current of flowing water." Fitts (2002) defines a spring more generally as "a place where groundwater discharges up to the ground surface." Similarly, Sharp (2023) defines a spring more generally as "a natural outflow of groundwater to the surface. It may be concentrated or diffuse." Kresic (2009) and Poehls and Smith (2009) distinguish springs from seeps by the presence or absence, respectively, of observable flow. In short, the authors do not agree on what is or is not a spring.

From the perspective of our fractal analysis, all springs used in our analysis had observable flows. However, when extrapolated and integrated, the fractal relationship extends well beyond "observable flows" and thus includes seeps (which, even if flow is not observable, there is still a flux of moisture from the discharge point).

Baseflow is also groundwater discharge, defined by Sharp (2023) as "groundwater flow to a surface water body (lake, swamp, or stream)..." Poehls and Smith (2009) describe baseflow as "due to groundwater seeping into the watercourse below its banks..." By these definitions, our analysis did not include subaqueous discharge (although in many cases springs contribute to flows in rivers and streams and often form the headwaters of rivers and streams). However, estimates of baseflow may provide an upper bound for total springflow since springflows make up part of total baseflows. In that case, Ward and Valdez (1995), in a chapter on the water budget for the state, estimated statewide natural groundwater discharge at 1.3 million acre-feet per year[5]. Anaya and others (2016) estimated total statewide baseflow at 9.3 million acre-feet per year.

Under pre-development conditions and a long-term dynamic equilibrium, anything that recharges an aquifer discharges from it. However, not all of that discharge expresses itself through springs and seeps to surface-water systems. Evaporative and phreatophytic discharge are also sources of discharge from groundwater discharge. Accordingly, recharge estimates—assuming they are perfectly correct (which they are not)—may represent an upper bound of groundwater discharge to surface water.

Ward (2011), based on numbers from Muller and Price (1979), estimated recharge at 5.5 million acre-feet per year. Muller and Price (1979) underestimates recharge since their estimates for confined aquifers focused on the component of recharge that flows down-dip in these aquifers and not the total amount. Anaya and others' (2016) baseflow estimate of 9.3 million acre-feet per year suggests that recharge is more than that. We compiled pre-development recharge amounts from the Texas Water Development Board's groundwater availability models and found 16.4 million acre-feet per year of recharge (Appendix). This number is consistent with the Anaya and others (2016) since it is greater than baseflow. However, total pre-development recharge from the models is still likely an underestimate since many of the models don't simulate all of the recharge and a couple aquifers are missing recharge volume estimates.

It's difficult to say which of these estimates is correct. Brune (1975) does not describe the logic he used in estimating 3 million acre-feet per year. Ward and Valdez (1995) did not provide information on where their estimate came from. Their estimate seems low, especially when compared to sums of springflows by Brune and us. Ward (2011) used recharge estimates from Muller and Price (1979), which are substantially larger than those in Ward and Valdez (1995). Anaya and others (2016) based their number on estimates of baseflow from Wolock (2003) and interpolation; however, base-flow separation can be fraught with difficulties (Young and others 2018a), and the dataset is part of a national analysis (Wolock 2003) that may miss regional and local details,

The dataset we used is not a fully accurate representation of springflows at a given time since measurements were made in different decades (Figure 12). Although we chose the highest recorded springflows for our fractal analysis to best represent pre-development conditions, the reality is that most springs have few measurements. Furthermore, the highest measured flows may not represent pre-development average flows. And a number of springs had already dried up before the Brune (1975) report. Regardless, the fractal nature of the data is strong enough to express itself despite these limitations.

Our fractal analysis may underestimate total groundwater discharge to surface water due to a bias for limestone terrains. According to Brune (1975), 139 springs issue from either the Edwards or Edwards-Trinity aquifers, and that does not include all springs that issue from limestones.

5 An update of this chapter by Ward (2011) indicates a groundwater contribution to surface water but does not quantify it.

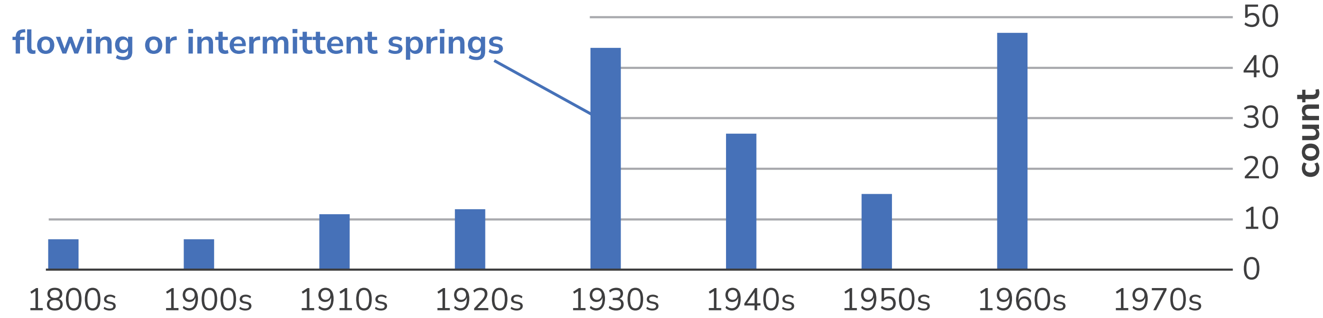

Figure 12. Number of the most recent springflow observations by decade (except for the 1800s, which represents the century) for flowing or intermittent springs in Texas for data presented in Brune (1975, 1981).

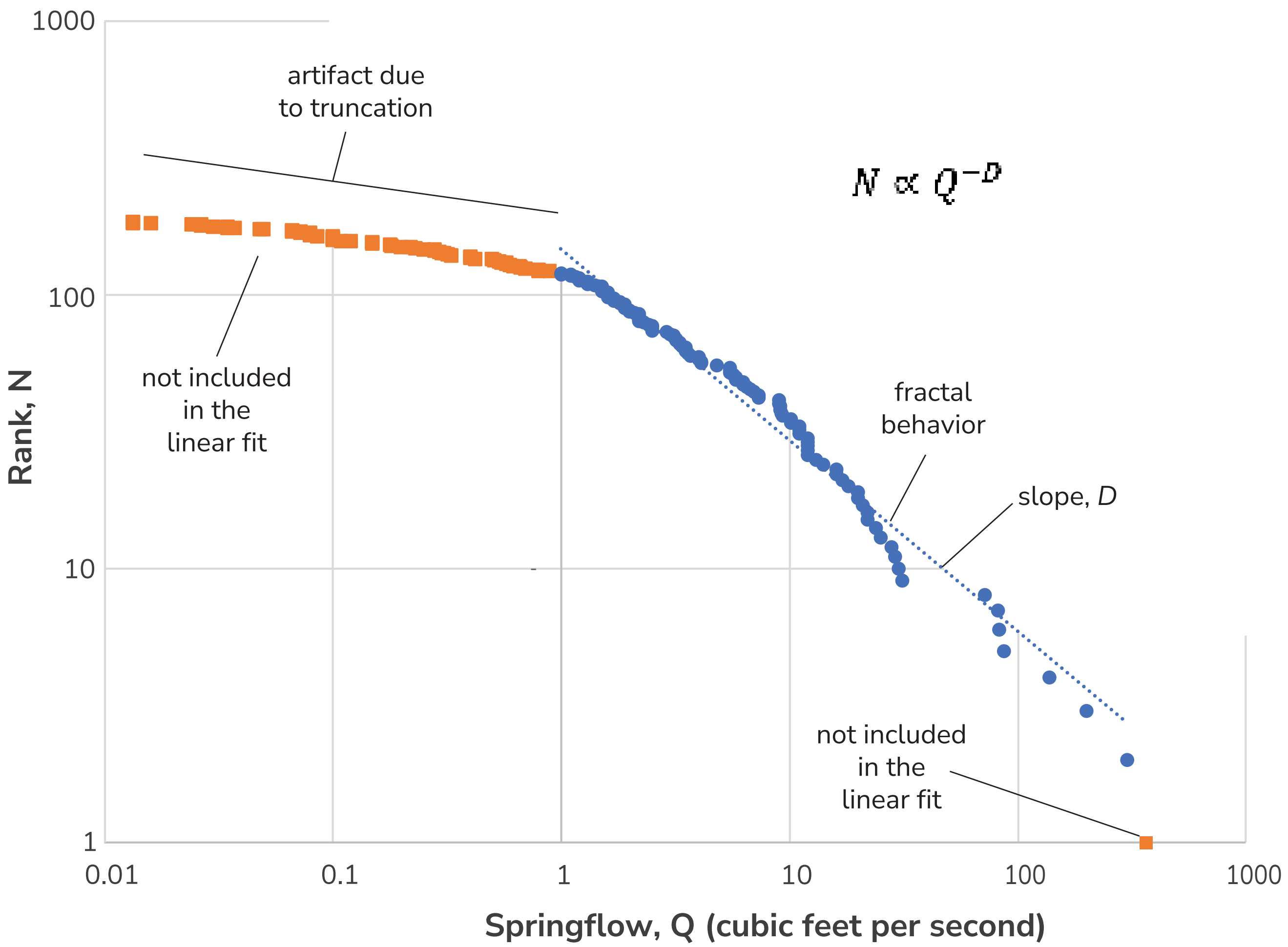

Figure 13. Power law plot of maximum reported springflow versus rank showing fractal behavior, a line fit, and the data used to fit the line.

Future Work

There are many opportunities to refine and expand on this work. Ideally, each of the springs evaluated would be visited in person to verify its flow status. We did the best we could with the tools we had, but we expect several or more of our evaluations will be proven incorrect with further research (on locations) and on-the-ground reconnaissance (for flow status). We are providing the database and this report as an updatable research tool available to the community. However, users of the information in this database tempted to ground-check springs need to respect private property rights.

A commentator at an early presentation of this work noted that aerial photography could offer a more detailed view of a spring's status over time, and we agree. With time, more satellite imagery will provide more information on spring status and, perhaps, an assessment of ephemerality.

Finally, our approach could be expanded to the springs in Brune (1981); however, that would be quite an effort since Brune, similar to his 1975 report, did not provide lat-long data for the springs in the book, and there is more than 10 times as many springs in the book.

Conclusions

We revisited the springs in Gunnar Brune's 1975 Texas Water Development Board report on the major and historical springs in Texas to determine how many more springs had gone dry from his work nearly 50 years ago. We found discrepancies in the flow status of springs between the 1975 report and the 1981 book. After correcting the flow status of springs in the 1975 report with those in Brune's 1981 book, we found that 14 percent of springs had gone dry by 1981, with 23 percent of those springs dry today, an increase in failed springs of 64 percent. Because Brune's book did not include the entire state and we found the book's spring status more reliable, we refined our analysis only to include those springs shared between the report and the book. This refined analysis showed that 11 percent of springs had gone dry by 1981 compared to 30 percent today, an increase of 173 percent, or 2.7 times more.

We also found that springflow volumes follow a power-law—or fractal—distribution with a fractal dimension of 0.72. Using the fractal relationship and correcting for a physical upper limit, we estimated total springflow in the state at 2.06 million acre-feet per year. This compares to Brune's speculation that total statewide springflow probably amounted to about 3 million acre-feet per year and to a range of estimates of groundwater discharge to surface in the state from 1.3 million to 9.3 million acre-feet per year.

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Appendix

AQUIFER	RECHARGE (acre-feet per year)	SOURCE
Blossom	70,469	Wade (2022, p 59)
Bone Spring-Victorio Peak	63,000	Hutchison (2008, p 148)
Brazos River Alluvium	96,344	Ewing and Jigmund (2016, p 3-64)
Capitan Reef Complex	347,845	Jones (2016, p 70)
Carrizo-Wilcox, Sparta, and Queen City (north)	639,673	Panday and others (2020, p 175)
Carrizo-Wilcox, Sparta, and Queen City (central)	1,200,042	Young and others (2018b, p 269)
Carrizo-Wilcox, Sparta, and Queen City (south)	224,170	Panday and others (2023, p 353)
Cross Timbers	-	Blandford and others (2021)
Edwards (north)	86,434	Jones (2023, p 49)
Edwards (Barton Springs)	43,438	Scanlon and others (2001, Table 6)
Edwards (San Antonio)	583,986	Lindgren and others (2004, p 75)
Edwards-Trinity (High Plains)	-	no recharge zone
Edwards-Trinity (Plateau) and Pecos Valley	1,209,000	Anaya and Jones (2009, p 80)
Ellenburger-San Saba	128,052	Shi and others (2016, C-3)
Gulf Coast (central and south)	6,724,511	Shi and Boghici (2023, p 3-33)
Gulf Coast (north)	654,172	Ellis and others (2023, p 297)
Hickory	16,592	Shi and others (2016, C-4)
Hueco Bolson	237	Heywood and Yager (2003, p 28)
Igneous and West Texas Bolsons	50,682	Beach and others (2004a, p 8-24)
Lipan	63,311	Beach and others (2004b, p 8-16)
Marathon	48,864	Blandford and others (2022, p 95)
Marble Falls	25,269	Shi and others (2016, C-2)
Mesilla Bolson	-	CH2MHill (2002)
Nacatoch	17,785	Beach and others (2009, p 8-19)
Ogallala and Dockum	902,949	Deeds and Jigmund (2015, p A-3)
Rita Blanca	-	no recharge zone
Rustler	3,896	Ewing and others (2012, p 8-13)
Seymour and Blaine	604,521	Ewing and others (2004, p 8-19)
Trinity (north)	1,766,567	Kelley and others (2014, p 8.2-5)
Trinity (south)	303,500	Jones and others (2011, p 114)
Yegua-Jackson	533,781	Deeds and others (2010, p 8-23)
Total: 16,409,090		

Groundwater availability modeling reports for aquifers with no recharge reported did not include volumetric recharge rates. Values shown are for steady-state, pre-development conditions. Some values include other formations represented in the model. Some models overlap each other; therefore, there may be double accounting of recharge amounts in several counties. The models do not include all recharge in the state and therefore underestimate statewide recharge. Recharge volumes are not reported for the Cross Timbers or Mesilla Bolson aquifers.

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