Estimation of Historical Pumping and Development of MODFLOW Well Package for the Northern Part of the Gulf Coast Aquifer in Texas, 1900 to 2018

Prepared for:

HARRIS-GALVESTON SUBSIDENCE DISTRICT

Harris-Galveston Subsidence District
1660 W Bay Area Blvd
Friendswood TX, 77546
(281) 486-1105

Prepared by:

INTERA GEOSCIENCE & ENGINEERING SOLUTIONS

INTERA Incorporated
Three Sugar Creek Center Blvd
Suite 675
Sugar Land, TX 77478
(281) 560-4560

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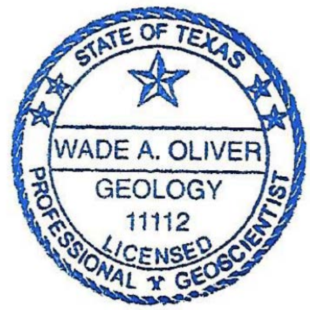

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1.0 INTRODUCTION

INTERA Incorporated ("INTERA") was retained by the Harris-Galveston Subsidence District ("HGSD") and the Fort Bend Subsidence District ("FBSD, together the "Districts") to assist with the development of historical pumpage estimates from the northern part of the Gulf Coast Aquifer for the period between 1900 and 2018 for incorporation into the **Gu**lf Coast **L**and Subsidence and Groundwater **F**low Model (GULF) 2023 groundwater model, which is being developed by the U.S. Geological Survey (USGS). The groundwater development history of the northern Gulf Coast Aquifer used to guide pumping estimates can be divided into two time periods based on data availability. The early period is from 1900 through 1974, during which time pumping estimates are only available from historical studies, primarily county-scale groundwater assessments. The availability of these studies increases over the period, with fewer available in the early 1900s than after 1950. The later period is from 1974 through 2018 when water use data from the TWDB, the Districts, and some GCDs are available. This report documents the process of collecting and analyzing relevant pumping information over these periods (detailed in Section 2) and the procedure used to associate pumping estimates to cells in the GULF 2023 groundwater model (detailed in Section 3).

2.0 HISTORICAL ANNUAL PUMPING ESTIMATES BY COUNTY

Historical annual pumping from the Gulf Coast Aquifer was estimated for each county within the active model domain (Figure 2-1). County pumping estimates were divided into seven use types: municipal, manufacturing/industrial, mining, irrigation, livestock, rural domestic, and power generation.

Pumping estimates between 1900 and 1974 were obtained from literature or estimated when literature values were unavailable. Water use survey data provided by the Texas Water Development Board ("TWDB") were used to obtain estimated historical pumping for the period 1974 through 2018 for the following use types: municipal, manufacturing, mining, power, irrigation, and livestock. Census data were used to estimate rural domestic pumping over the entire study period. Table 1 below summarizes and the following subsections describe the available data and assumptions used to estimate pumping for each of the use types through time.

Table 2-1. Summary of primary data sources informing water use estimates for each use type

<table>
<tr><th rowspan="2">Use Types</th><th colspan="2">Primary Data Source Informing Water Use Estimate</th></tr>
<tr><th>1900-1974</th><th>1975-2018</th></tr>
<tr><td>Rural Domestic</td><td colspan="2">Developed using census block population, estimated population density to define rural areas, and estimated per capita usage over time.</td></tr>
<tr><td>Municipal</td><td>Census-based estimate reconciled with historical reports.</td><td rowspan="7">TWDB estimates outside of Harris, Fort Bend, and Galveston Counties and reported data inside these counties.</td></tr>
<tr><td>Industrial / Manufacturing</td><td rowspan="3">Very limited data, interpolated when literature estimates were available.</td></tr>
<tr><td>Power</td></tr>
<tr><td>Mining</td></tr>
<tr><td>Irrigation</td><td>USDA-based estimates reconciled with other historical reports.</td></tr>
<tr><td>Livestock</td><td>USDA cattle population estimates and assumed cattle usage rates.</td></tr>
</table>

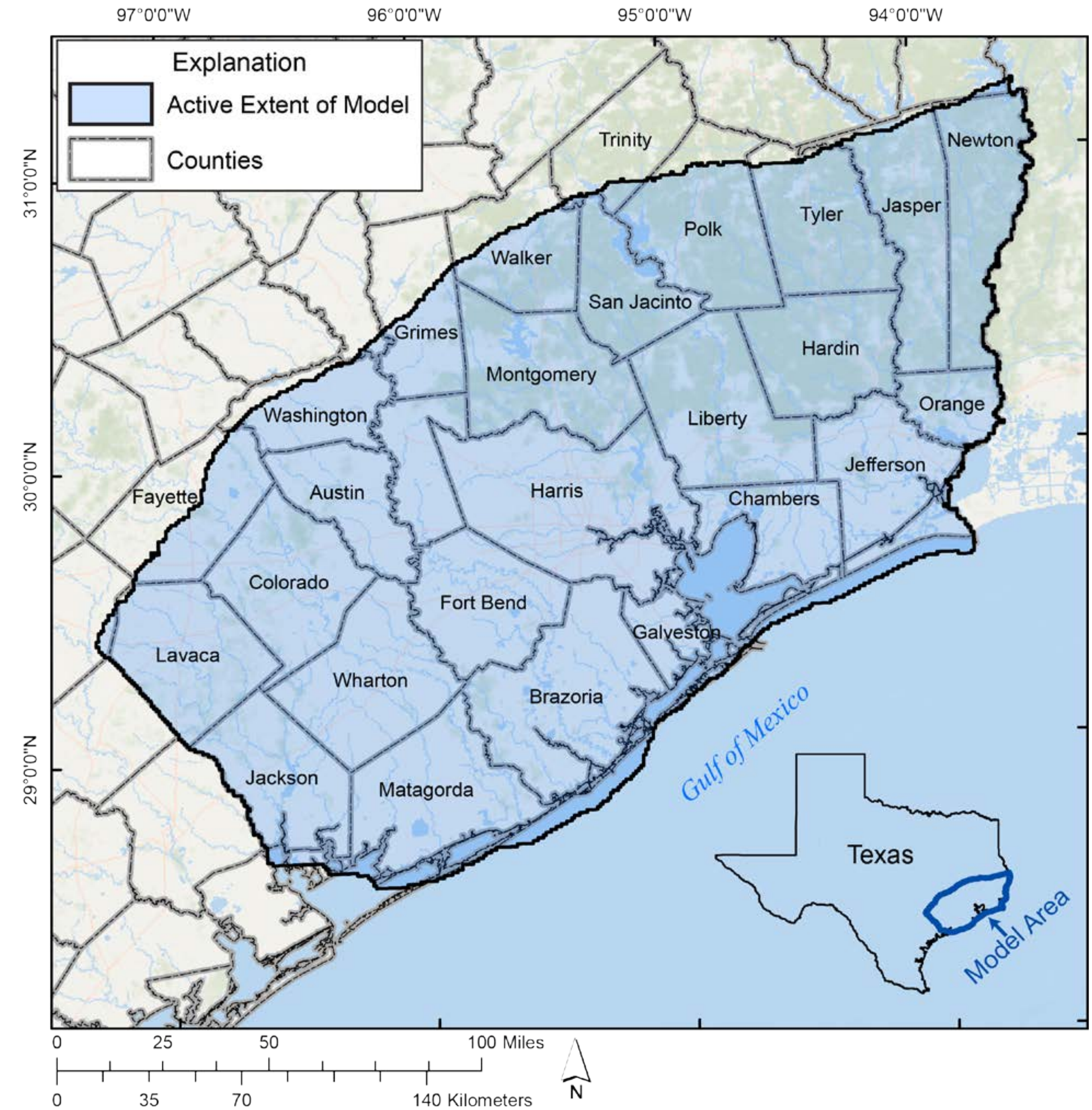

Figure 2-1. The northern part of the Gulf Coast Aquifer that is considered “active” in the GULF 2023 numerical groundwater model

2.1 Literature Sources of Historical Pumping

Sources reviewed for historical estimates of pumping from the Gulf Coast Aquifer include reports available through TWDB and USGS. A summary of these sources, including their area, period of interest, and the type of pumping information available, is provided in Table 2-1. The types of historical reports include regional hydrogeologic studies, studies of groundwater resources in individual counties, summaries of historical municipal water use, and water supply investigations conducted at the request of municipalities. In general, the earliest reports, which typically address local groundwater issues, provide pumping estimates for a single year at a county scale. The reports related to regional hydrogeologic investigations provide the most data with respect to pumping for multiple use types and estimates for multiple years.

Early reports mention that there were some flowing wells present in the 1800s and early 1900s, though information on the number, location, and quantities discharged from flowing wells was undocumented and is very uncertain. Common practice by early well owners was to allow water to freely discharge from flowing wells, which could have resulted in large volumes of groundwater loss and reduction in water levels. Because of the uncertainty associated with flowing wells, their potential influence was not incorporated into pumping files. The reports of flowing wells generally predate subsidence and water level monitoring. It the author's expectation that this known limitation of early 1900s information is unlikely to significantly impact the quality of fit to subsidence and water level trends in the model.

Table 2-2. Historical reports reviewed for estimates of pumping.

Source	County	Aquifer	Period of Record	Use[a]
Wilson (1967)	Austin, Waller	Evangeline, Jasper, Brazos River Alluvium	1930-1965	IND, IRR, MUN, RD, STK
Wesselman and Aronow (1971)	Chambers, Jefferson	Chicot, Evangeline	1926, 1927, 1941, 1965	IND, MUN, IRR
Loskot and others (1982)	Colorado	Chicot, Evangeline	1901-1974	IND, IRR, MUN
Rogers (1967)	Fayette	-	1955-1964	MUN, IND, RD, STK
Thorkildsen (1990)	Fort Bend	-	1980, 1985	IND, IRR, MUN, RD, STK
White and Others (1942)	Fort Bend	-	1930, 1935, 1937, 1939-1941	IRR
Gabrysch (1984)	Galveston	-	1960-1978	IND, MUN
Baker and Others (1974)	Grimes	-	1942-1970	IRR, MUN, RD, STK
Baker (1964)	Hardin	-	1943-1962	IND, IRR, MUN, RD, STK
Gabrysch (1984)	Harris	-	1960-1978	IND, MUN
Michel (2006)	Harris	-	1976-2004	IND, MUN, IRR
Seifert and Drabek (2006)	Harris and Galveston Counties	-	1890-2004	TOT
Baker (1965)	Jackson	-	1934-1963	IND, IRR, MUN
Wesselman (1967)	Jasper and Newton Counties	Chicot, Evangeline	1940-1965	IND, IRR, MUN, RD
Loskot (1982)	Lavaca	Evangeline, Chicot, Jasper	1948-1974	IND, IRR, MUN
Anders and Others (1968)	Liberty	-	1943-1965	IND, IRR, MUN, RD, STK
Hammond (1969)	Matagorda	-	1946-1966	IND, IRR, MUN, RD, STK
Popkin (1971)	Montgomery	Chicot, Evangeline, Jasper	1850, 1900, 1940, 1966	IND, IRR, MUN, RD
Bonnet and Gabrysch (1983)	Orange	Chicot	1963-1979	MUN, IND
Wesselman (1965)	Orange	Chicot	1941, 1955, 1958, 1962	IND, IRR, MUN, RD, MIN
Thorkildsen and Quincy (1990)	Orange	-	1980, 1985	IND, MUN, IRR, RD, STK
Alexander (1947)	San Jacinto	-	1906-1947*	IND, MUN, IRR, RD, STK
Tarver (1968)	Tyler	-	1964	MUN, IND, RD, STK
Loskot and others (1982)	Wharton	Chicot, Evangeline	1901-1974	IND, IRR, MUN
No available literature estimates for Brazoria, Polk, Walker, and Washington Counties.				

[a] Use Codes: TOT = total groundwater use estimate, IND = industrial, IRR = irrigation, MFG = manufacturing, MIN = mining, MUN = municipal, PWR = power, RD = rural domestic, STK = livestock
*Partial record, - No record

2.2 Historical Pumping Estimates for 1900 through 1974

Estimates of historical pumping by county between 1900 and 1974 were based on literature values when available and estimated using other approaches when literature values were unavailable or determined to be unreliable. Historical pumping in the study area could be estimated using census and U.S. Department of Agriculture information for municipal, rural domestic, livestock, and irrigation purposes. Estimates could not be developed using these approaches for mining, manufacturing/industrial, and power generation purposes. Where literature estimates for mining, manufacturing/industrial, and power generation pumping existed, they were incorporated into the annual pumping estimates.

Time series plots showing historical pumping estimates from the literature or estimates developed from related datasets (e.g., the census) were created for each county as shown in in Figure 2-2 and Appendix A. For sources with estimates for multiple use types, the sum of pumping for all types was plotted. The historical estimates from these time-series plots were reviewed and integrated to estimate annual pumping by use type by county. The following subsections describe how historical groundwater pumping estimates were developed for rural, municipal, livestock, and irrigation purposes.

2.2.1 Rural Domestic and Municipal Pumping Estimates

The basis for the municipal and rural domestic pumping estimates was population data between 1900-2010 (U.S. Census Bureau), population density distributions associated with census blocks (Manson and others, 2020), and assumed per capita use rates. The U.S. Census Bureau provides historical county populations for every census year from 1850 to 2010. For intermediate years, a linear change in population was assumed. The total county populations were divided into urban and rural populations using population densities from census block data and an assumed population per area threshold (discussed in more detail below) used to differentiate rural vs. urban areas. The historical municipal and rural domestic water use was calculated as the population times the per capita use rates for each year. These calculations represent total use for the county and do not distinguish between the sources of water (groundwater or surface water). The split of use between surface water and groundwater for the municipal pumping calculations prior to 1974 was assumed to be the same as that in 1974, which is the earliest year with available data on how much of the water for municipal use was supplied by surface water sources and how much was supplied by groundwater sources.

Per-Capita Municipal and Domestic Use Estimates

The per-capita use rate was assumed to be lower in the early 1900s than in the latter half of the study period for both rural and urban populations. To estimate the historical per-capita use rate for the municipal calculations, an estimate of the current use rate was first developed. Using the county populations and municipal use provided by TWDB for the years 1974 and 1980, the per-capita use rate was calculated for each of these years for each county as the municipal use divided by population. The average of these was used to represent the per-capita use rate in prior years. The historical municipal per-capita use rate for urban areas was calculated individually for each county and was assumed to be 25 percent of the rate in 1900, 50 percent of the rate in 1950, and 95 percent of the rate in 1974. The per-capita use rate for the intermediate years was calculated assuming a linear increase. This method has been applied in other areas within Texas (e.g., Kelley and others [2014].

The historical per capita use rates for rural areas were assumed to be the same for all counties. Estimated rates were assigned for 1900 and each decade thereafter. The assumed rates at these times are listed in Table 2-2 and assume an increase in use per capita throughout the 1900s. Between these decadal years, the per capita rate was increased linearly. As with municipal use above, this approach has been used elsewhere in Texas (Kelley and others, 2014).

Table 2-3. Assumed per capita use rates assumed for rural domestic calculations.

Year	Assumed Per Capita Use (gallons per day)
1900	25
1910	35
1920	35
1930	40
1940	50
1950	65
1970	75
1980	100
1990	100
2000	100
2010	100
2018	100

Rural and Urban Population Density Estimates

The spatial distribution of rural and urban populations prior to 2000 was informed using the census block population density distributions from the year 2000, the earliest time spatial population distribution data was available for the entire active model domain. The census blocks from 2000 were scaled so that the total population of all census blocks within a county equaled the historical county population reported by the U.S. Census Bureau. The scaled census block data was associated with the GULF 2023 model grid, yielding the number of people per model cell (each cell is one square kilometer) for every year between 1900 and 2018. A threshold value of 100 people per square kilometer was used to distinguish between rural and urban model cells. The United States Department of Agriculture ("USDA") defines rural areas as open countryside with population densities less than 500 people per square mile or approximately 193 people per square kilometer. Using a threshold of 193 people per square kilometer resulted in an overestimate of rural population, which led to an overestimate of rural pumping and an underestimate of municipal pumping when compared to available literature estimates. Reducing the threshold to 100 people per square kilometer led to rural and municipal pumping estimates that were more aligned with literature pumping estimates.

For the calculations of historical rural domestic pumping, the assumption was made that the source of water to rural domestic wells is the aquifer that outcrops at the location of the well. Therefore, the split between aquifers was based on the spatial distribution of outcrop areas within each county. The process used to associate municipal pumping with a specific aquifer is detailed in Section 3 below.

2.2.2 Livestock Pumping Estimates

The calculations to estimate historical livestock pumping were based on agriculture census cattle population data available from the USDA and an assumed per-animal use rate. Available agricultural census data for each county collected in the years 1924, 1939, 1944, 1949, 1954, 1959, 1964, 1969, and 1974 were used to estimate dairy cattle and beef cattle populations. For years between census years, the cattle populations were assumed to change linearly. A constant per-animal use rate was assumed throughout time. The selected rate was based on cattle type such as dairy or beef. Dairy cattle have a higher water need than beef cattle. The assumption was made that dairy cows consume 45 gallons of water per day and beef cattle consume 15 gallons of water per day (Kelley and others, 2014). The historical livestock water use was calculated as the estimated cattle population times the estimated per-animal use rate. These estimates represent total use for the county and do not distinguish between the sources of water (groundwater or surface water) or the source aquifer for groundwater. Using the estimates of surface water and groundwater use for livestock purposes in 1980 obtained from TWDB, the percentage supplied by groundwater was calculated for each county. That percentage was applied to years prior to 1980 as the best estimate available for the percent of water use for livestock purposes supplied by groundwater.

For the calculations of historical livestock pumping, the assumption was made that the source of water to livestock wells is the aquifer or formation that outcrops at the location of the well. Therefore, the split between aquifers for these calculations was based on the spatial distribution of outcrop areas within each county. The total pumping for livestock purposes was calculated as the product of the county cattle population, the per animal use, the groundwater fraction, and the aquifer fraction. Livestock use between 1900-1924 was assumed to be equal to livestock use in 1924 as no earlier agriculture census information was available.

2.2.3 Irrigation Pumping Estimates

TWDB (2001) provides estimates of groundwater use for irrigation purposes for the years 1958, 1964, 1969, 1974, and 1979. That report provides estimates of irrigated acreage and groundwater applied as irrigation for each of these years in each county in Texas. Irrigated acreage for additional years is available in the USDA agricultural census for the year 1909, 1919, and 1939. Using the data from TWDB (2001), a methodology was developed to estimate the average irrigation depth (i.e., total crop water need divided by total irrigated acreage) for each county and apply that depth to the irrigated acreage for the years 1909, 1919, and 1939. This methodology enabled estimation of water use for irrigation purposes back to 1909. Estimated irrigated acreage was also available for 1949 and 1954, though county estimates of irrigated acreage for these years were significantly greater than years prior and greater than irrigation values reported by TWDB in 1958 and 1964. For these reasons, irrigated acreage values from the USDA for 1949 and 1954 were removed from the analysis.

The methodology used to estimate irrigation water use also has a correction factor to account for any precipitation, which is assumed to offset the need for irrigation. Annual precipitation estimates were available at a one square mile resolution from the PRISM dataset through Oregon State University (https://prism.oregonstate.edu/) for years between 1900 and 1958. With the TWDB (2001) reported estimates of total irrigation water use and the corresponding reported irrigated acreage for years 1958, 1964, 1969, 1974, and 1979, an average irrigation depth was calculated for each county. The average irrigation depth for each county, which was assumed to be applicable in years prior to 1958, was multiplied by the reported irrigated acreage from the agricultural census for 1909, 1919, and 1939.

The calculation above provided the total water required but did not distinguish the source of water (groundwater or surface water) or the source aquifer for groundwater. The groundwater/surface water split was calculated using data published in TWDB (2001). That report provides total water use and groundwater use for irrigation purpose in census years. Using these data, the fraction of total water used for irrigation purposes sourced from groundwater was calculated for each census year. The average groundwater portion was then applied to the total water use estimated for years 1909, 1919, and 1939 to estimate the groundwater use for irrigation purposes. Groundwater use for irrigation purposes between census years was calculated assuming a linear change between years. Irrigation prior to 1909 was assumed to be equal to irrigation water use in 1909.

2.3 Historical Pumping Estimates from 1974-2018

Estimates of historical pumping from 1974, 1980, and 1984 to 2018 were obtained from TWDB for municipal, manufacturing/industrial, mining, power, irrigation, and livestock water use categories (TWDB, 2021). These water use estimates were developed to support state water planning and the TWDB Groundwater Availability Model ("GAM") program. Pumping estimates for 1974-1980 and 1980-1984 were linearly interpolated. Estimates of historical pumping for rural domestic purposes for 1974 through 2018 were calculated using census block data and the method described in Section 2.2.1.

2.4 Reported Pumping

Reported pumping is available from the subsidence districts and some groundwater conservation districts (GCDs) within the model area over recent decades. HGSD has been collecting reported pumping since 1976 and FBSD began annual collection in 1990. Lone Star GCD started to collect reported pumping data in 2002. In this study, when reported pumping data was available it was given priority over water use survey estimates submitted to TWDB because of the additional detail contained in the reported pumping information. Section 3.2 details how reported pumping data was incorporated into the well file.

2.5 Combined Historical Pumping Estimates for 1900 to 2018

This section presents the combined estimated historical pumping from all sources between 1900-2018. The combined pumping estimates are shown as stacked bar charts of pumping by use category, which were developed for each county that pumps from the northern Gulf Coast Aquifer for the period between 1900 and 2018 (Appendix B). The bar charts are useful for visualizing total pumping trends and trends of pumping for individual use categories. When comparing the plots, note that the scale of the x-axis is constant from 1900 to 2018 but the scale of the y-axis varies from plot to plot based on the estimated historical volumes pumped.

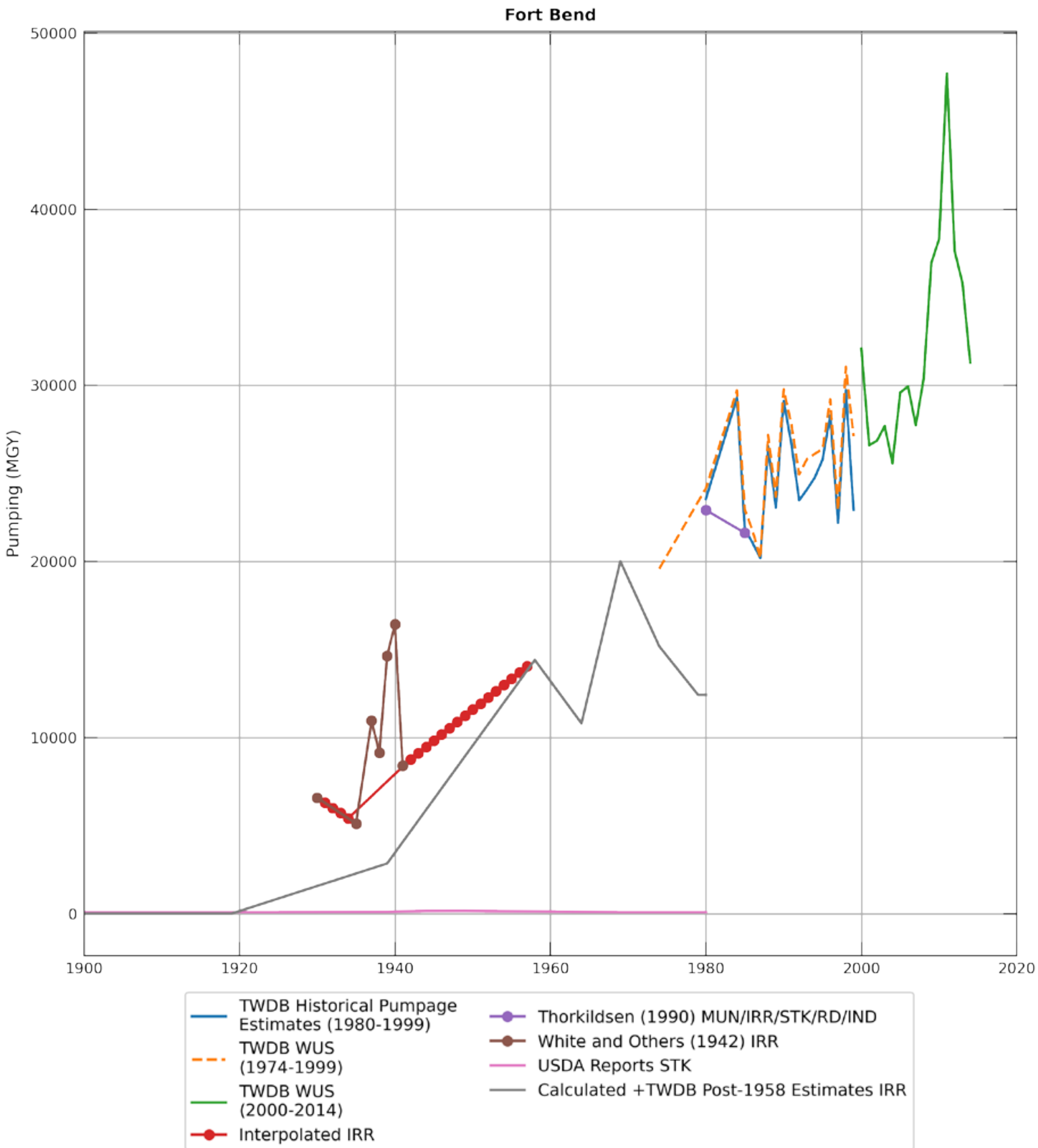

Figure 2-2. Time series plots showing historical pumping estimates from the literature and TWDB for Fort Bend County. Units are in million gallons per year (MGY).

3.0 IMPLEMENTATION OF PUMPING

Implementation of pumping in a groundwater model requires definition of the spatial and temporal volumetric flow rate. Spatially, the volume of groundwater withdrawn from each grid cell in each layer must be defined. Temporally, pumping must be consistent with the stress periods of the model. The estimated annual historical pumping on a county scale for all use categories presented in Appendix B must be made consistent with the spatial and temporal scales of the groundwater model. This process is referred to here as pumping implementation. The distribution of pumping to model grid cells was completed differently depending on the water use category, the stress period and the availability of reported data. A flow chart summarizing the process of pumping implementation is included as Figure 3-1.

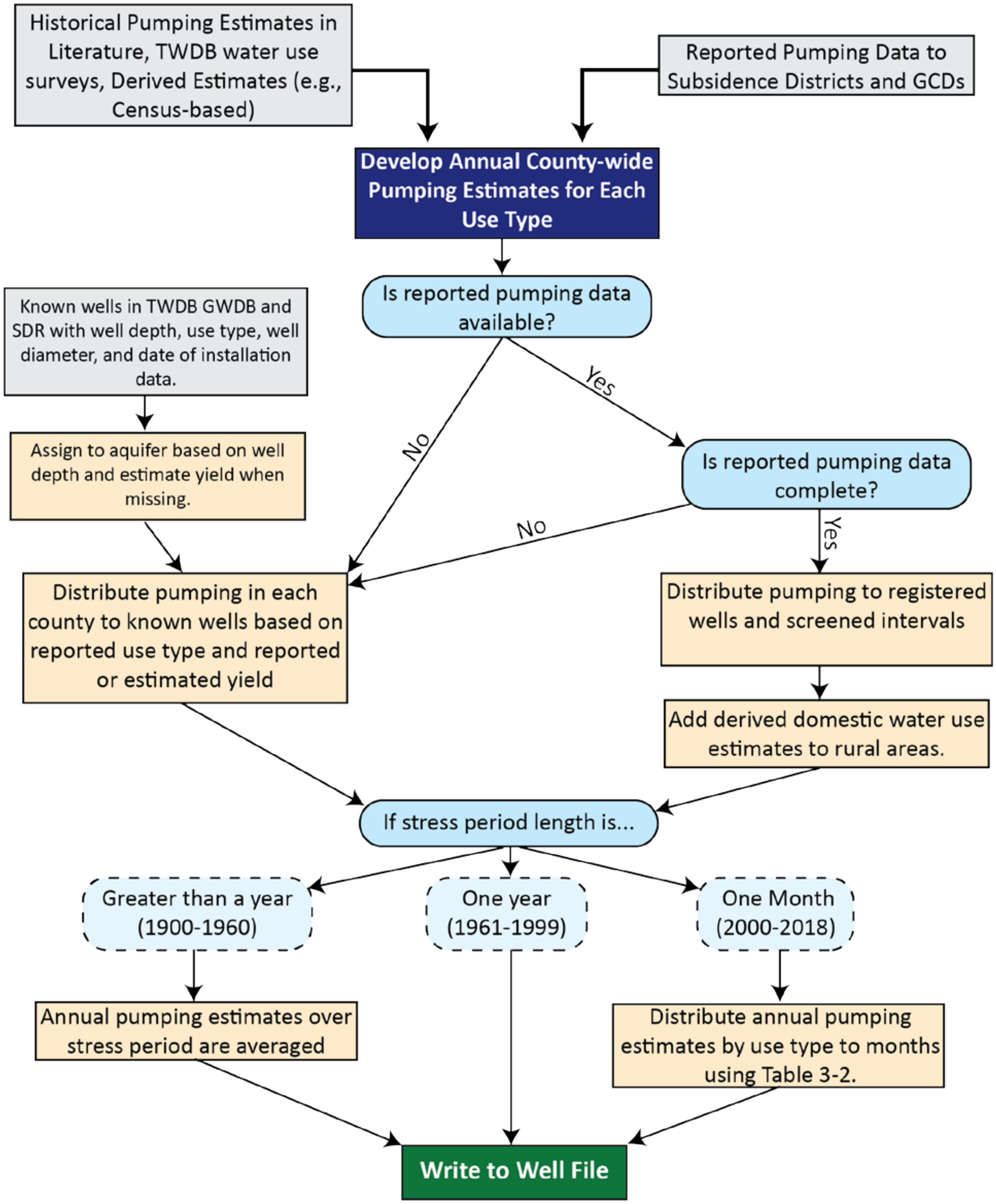

Figure 3-1. Flow chart of pumping implementation process.

3.1 Pumping Implementation in Counties without Reported Data

For counties without pumping data reported to groundwater management entities, the pumping for water use categories manufacturing/industrial, power generation, mining, livestock, irrigation, and municipal was distributed among wells with a corresponding reported use type and was proportioned based on the reported/estimated well yield. If well yield was not reported and available in the TWDB Groundwater Database or Submitted Drillers Reports Database, a well yield was estimated using a multiple linear regression that relates well diameter, well depth, and well yield (Figure 3-2).

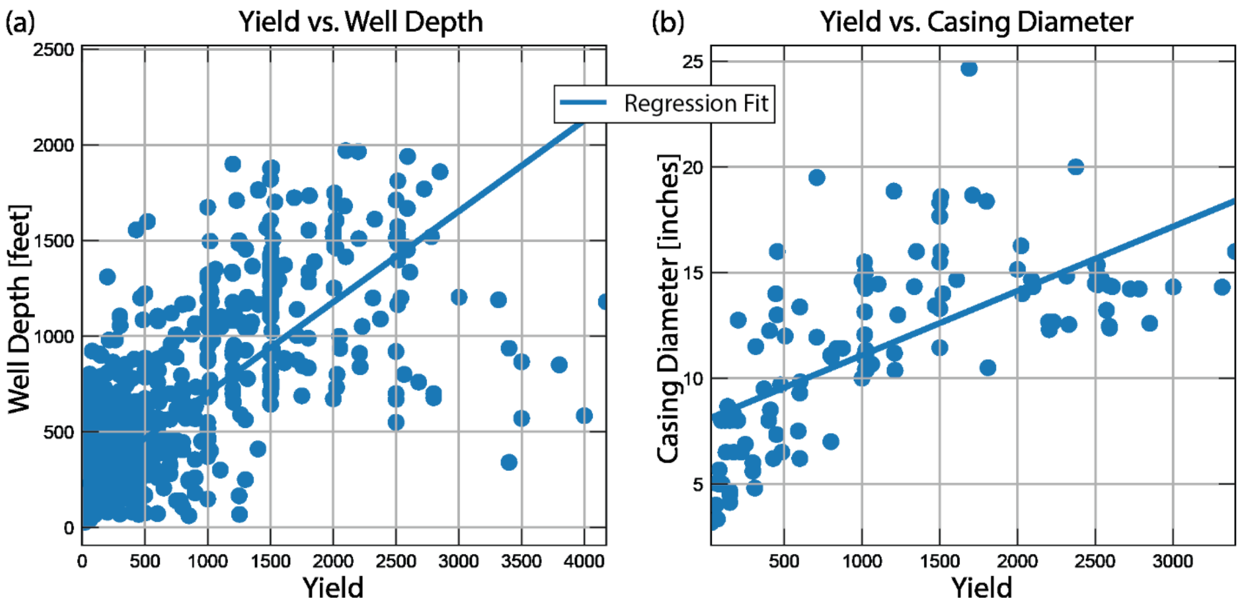

Figure 3-2. Multiple linear regression that relates well diameter, well depth, and well yield.

Prior to 1980, when limited well information was available, pumping estimates for municipal, manufacturing/industrial, and/or irrigation would sometimes exceed the total capacity of all known wells (determined by summing estimated well yields) in some counties. In counties where this excess was for municipal and manufacturing/industrial uses, excess pumping was distributed uniformly across grid cells associated with the top-most aquifer and designated as urban based on the census data. Excess irrigation pumping was uniformly distributed across grid cells associated with the top-most aquifer and identified as rural. For all other use types, county estimates did not exceed the capacity of the known existing wells at that time.

Pumping volumes associated with wells were assigned to co-located grid cells. Vertically, well pumping volumes were assigned to aquifers using total well depth because limited well screen information is available for most wells. Aquifer assignments in wells less than 250 feet were based on the aquifer present at 80% of the total well depth. For example, in a well that is 100 feet deep, the well would be assigned to the aquifer located 80 feet below ground surface. Wells with a total depth greater than 250 feet were assigned to the aquifer unit located 50 feet above the bottom of the well. This approach was taken to associate the well with the aquifer most likely to be screened by the well.

3.2 Pumping Implementation in Counties with Reported Data

To incorporate the Districts reported pumping data into the pumping estimates we 1) allocated the measured annual pumping from each permitted well to the aquifer layer(s) it was in contact with, and 2) distributed well pumping to each aquifer layer in the model grid based on the latitude and longitude of each well. Surface elevations were determined for each well using the USGS digital elevation model (USGS, 2021). The reported pumping data included the depth to the first well screen and the total depth of each well. For distributing the pumping, we used the length of the well column between these two points that intersected one or more aquifers. For example, if 20% of the column between the top of the first well screen and the well bottom intersected the Chicot Aquifer, then the Chicot Aquifer would be assigned 20% of the pumping from that well each year.

Pumping is also reported to the Districts by permit, not by well. For permits that are associated with multiple wells, the reported pumping is divided evenly among the active wells each year. While we recognize this is not a perfect assumption, we believe it appropriate and the best possible approximation for the purposes of this study.

For years that preceded reported pumping, the quantity of reported pumping from the earliest year available (e.g., 1976 in HGSD and 1990 in FBSD) was scaled to the total county pumping estimate (i.e., the sum of all pumping use types) developed using the processes detailed in Section 2.3. The pumping spatial distribution from 1976 in HGSD and 1990 in FBSD was held constant for years that preceded reported pumping data. The spatial distribution was held constant so there could be a seamless transition from county pumping estimates that predated reported data to periods with reported pumping data. For example, Figure 3-3 shows the Harris County annual pumping estimates (bars), the total reported pumping amount for years 1976-2018 (black dots), and the total volume of pumping implemented in the pumping file (dark blue line). Post-1976 pumping estimates are approximately equal to the total reported pumping in Harris County, while years prior to 1976 implemented pumping scaled to equal county estimates.

The pumping implementation process used in the Districts could not be applied to LSGCD (Montgomery County) because reported pumping in LSGCD was significantly less than the total pumping known to occur from other sources such as the TWDB Water Use Survey. Reported pumping from LSGCD was incorporated if the total within a grid cell was at least 50% greater than the proportion of total county pumping assigned to that grid cell and the neighboring eight grid cells using the methods described in Section 2.1. This was done to ensure that known centers of concentrated and metered pumping were incorporated into the pumping dataset without double accounting even if the metered pumping was not sufficient to be the primary data source.

3.3 Annual Pumping Estimates to Model Stress Periods

Annual pumping estimates were scaled to fit the stress period lengths defined in the GULF 2023 model (Table 3-1). Between 1900 and 1961 the stress periods consist of multiple years (e.g., stress period 1 is 11 years in length and corresponds to the period between 1900-1911). Pumping assigned to multiyear stress periods was the average annual pumping that occurred over the given stress period.

Stress periods 41-267 are monthly stress periods, so annual pumping estimates had to be scaled to match the monthly stress periods. This was achieved by proportioning annual pumping estimates to monthly use based on the percentages listed in Table 3-2. This information was developed using information on municipal and industrial intakes by month in Region H Regional Water Planning Area (TWDB, 2021). Mining, power, and livestock use categories were assumed to be constant over the period. The irrigation estimate was developed assuming an approximately 5-month irrigation season. The rural domestic proportions were assumed to be the same as the municipal estimates.

Table 3-1. Stress periods defined in the GULF 2023 model.

Stress Period(s)	Period	Time Step	Pumping Scaled to:
1	1900-1911	11 years	Average over stress period
2,3	1911-1937	13 years	Average over each stress period
4-9	1937-1961	4 years	Average over each stress period
10-40	1961-2000	1 year	Scaling of annual pumping estimates was not needed
41-267	2000-2018	Monthly	Annual estimates scaled by monthly use factor for each use type

Table 3-2. Proportions of annual pumping occurring in each month by use type.

Month	Municipal	Industrial	Mining	Power	Irrigation	Stock	Domestic
January	7%	8%	8%	8%	0%	8%	7%
February	7%	7%	8%	8%	0%	8%	7%
March	8%	8%	8%	8%	0%	8%	8%
April	8%	8%	8%	8%	0%	8%	8%
May	9%	9%	8%	8%	20%	8%	9%
June	9%	9%	8%	8%	21%	8%	9%
July	10%	10%	8%	8%	21%	8%	10%
August	10%	10%	8%	8%	20%	8%	10%
September	9%	9%	8%	8%	18%	8%	9%
October	9%	8%	8%	8%	0%	8%	9%
November	8%	8%	8%	8%	0%	8%	8%
December	8%	8%	8%	8%	0%	8%	8%

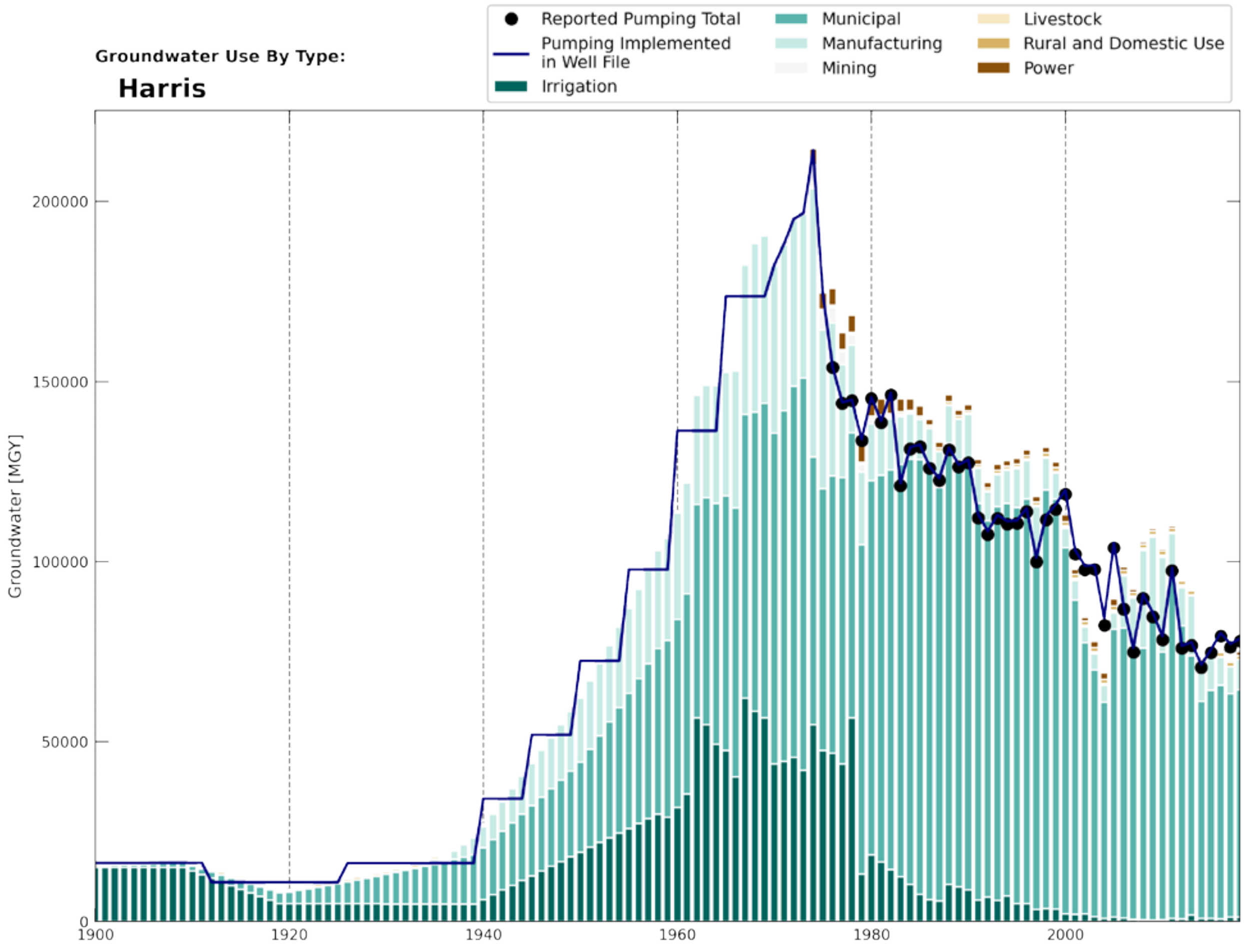

Figure 3-3. Pumping estimates for Harris County. Bar plot shows pumping estimates by use type from 1900-2018.

4.0 UNCERTAINTY AND LIMITATIONS

The recreation of the history of groundwater pumping over more than 100 years is inherently an uncertain process due to limited and evolving recordkeeping. As described in the introduction, the development history of the northern Gulf Coast Aquifer can generally be divided into two periods. The first period, 1900 through 1974, has intermittent county level pumping estimates sourced from local groundwater studies (Table 2-1). The later period between 1974 and 2018, has more robust annual data from the TWDB, the Districts, and data from some GCDs. These periods are clearly discernible on the pumping curves developed by county (Figure 2-2) and presented in Appendix A. Historical data on pumping volumes are greater for the period from 1940 to 1974 than for the pre-1940 period. For this reason, estimates of pumping developed by the TWDB for 1974 were used to check consistency in the pumping time series as it approaches 1974. During the period from 1940 to 1974, pumping uncertainty is seen in the variability of historical pumping estimates provided from various sources. This variability is generally 20 to 25 percent and, in some counties, reached 50 percent. For the final period, 1974 through present, estimates of historical pumping are available from the TWDB water use survey data and from the Districts and GCD production data. Because of the increase in data quantity and quality over the final period, there is greater confidence in more recent pumping estimates.

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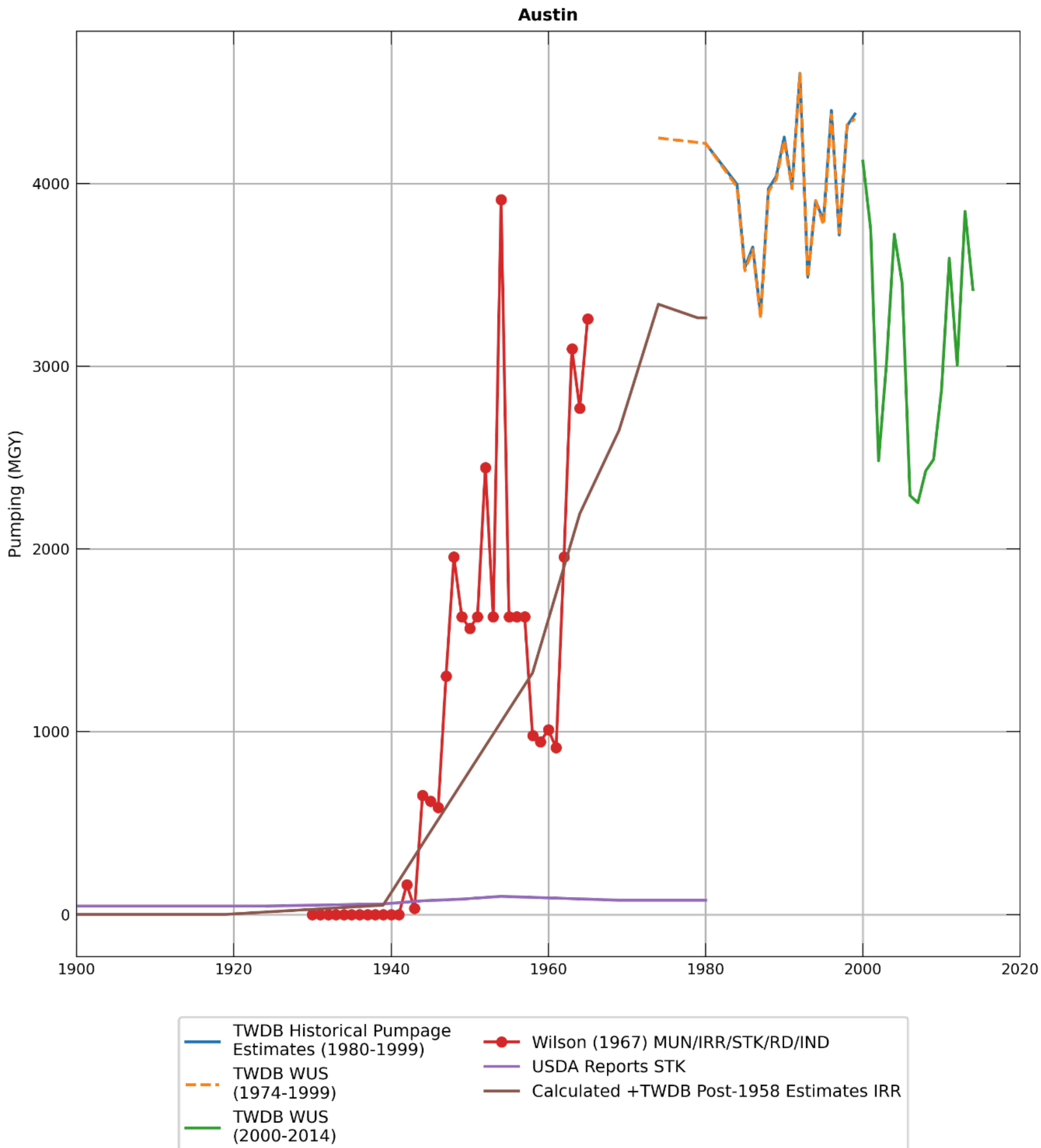
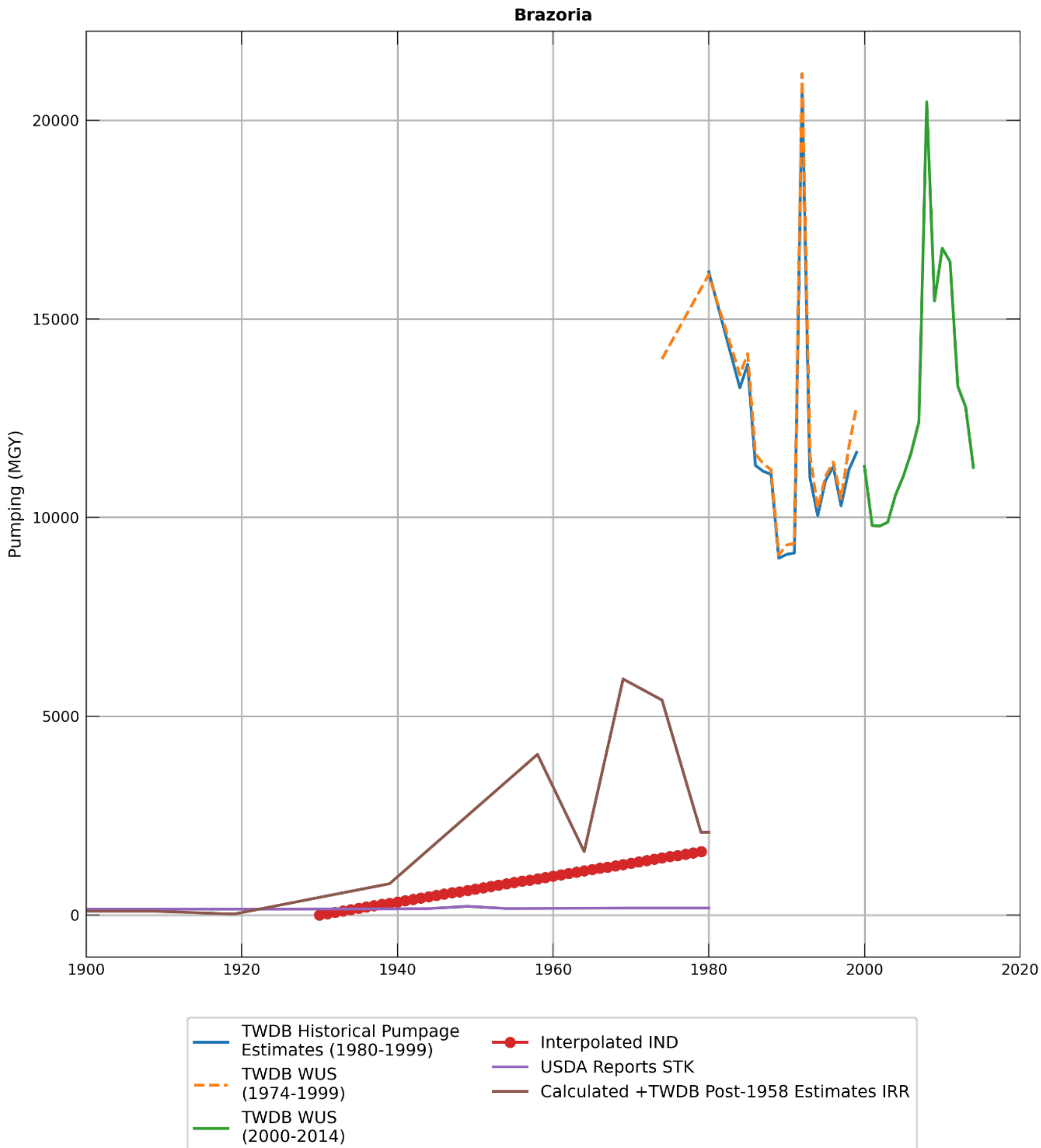
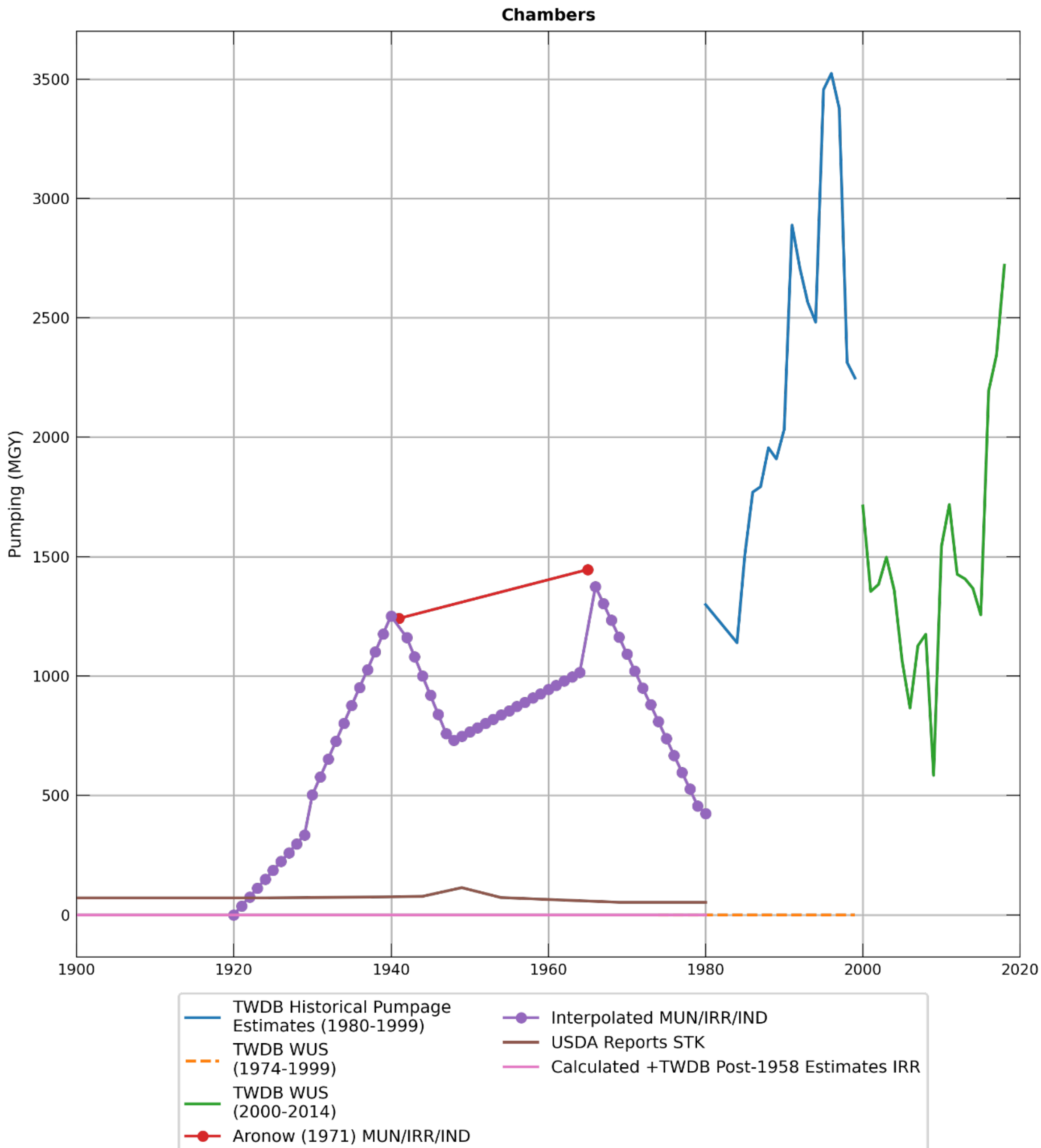
APPENDIX A:

LITERATURE ESTIMATES OF COUNTY PUMPING FOR EACH USE TYPE

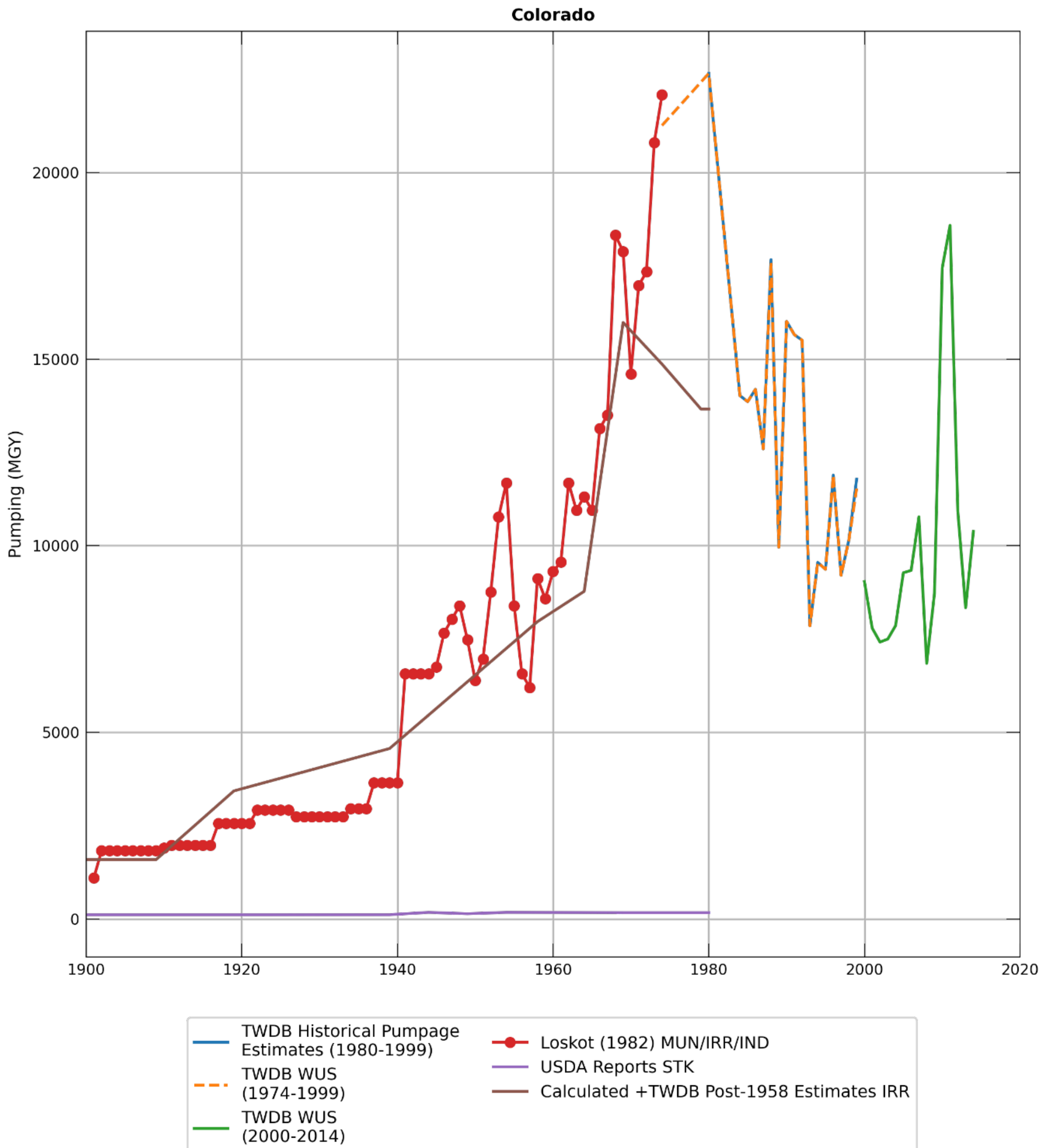

Austin
Pumping (MGY)
4000
3000
2000
1000
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Wilson (1967) MUN/IRR/STK/RD/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR



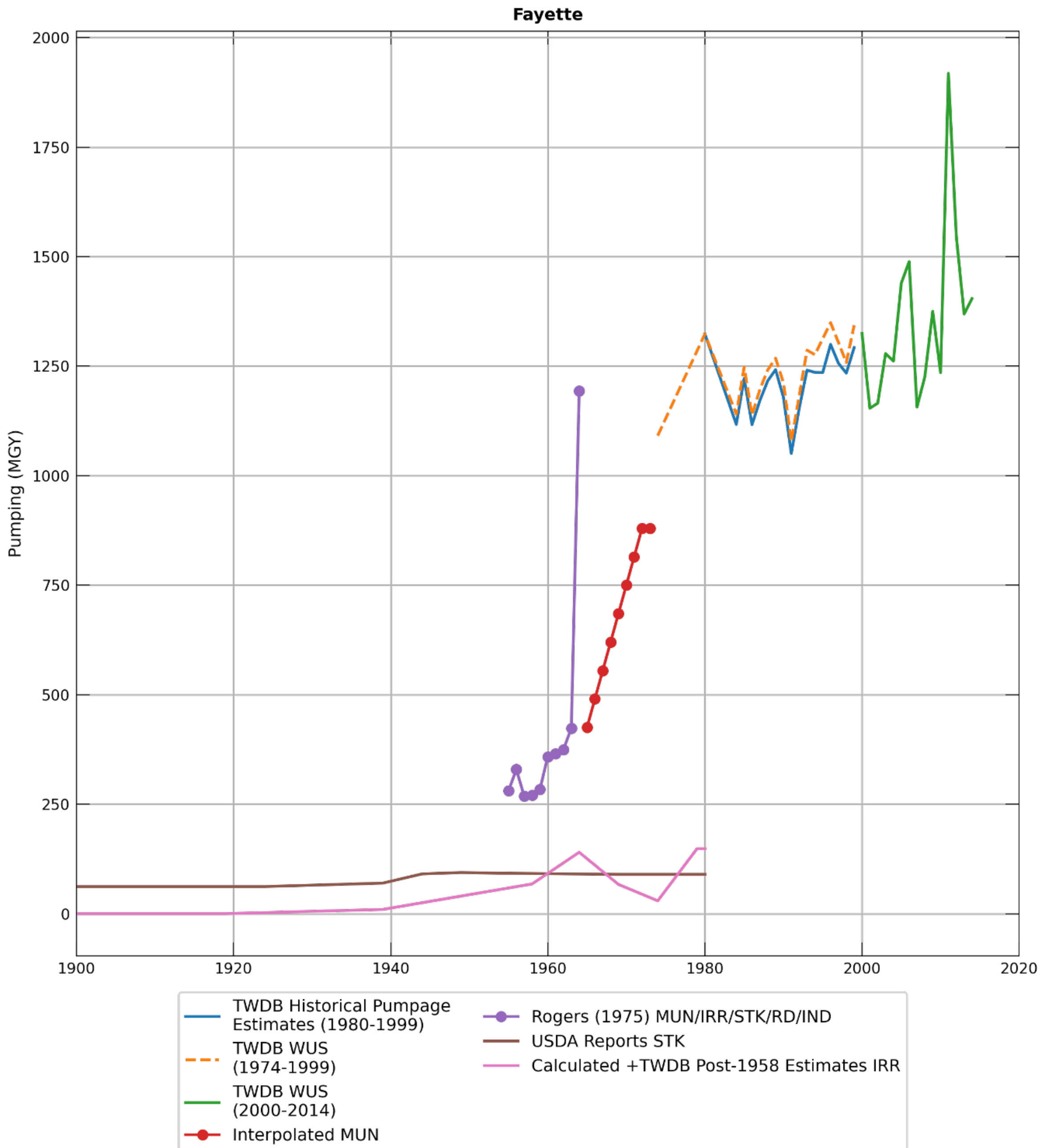
Brazoria
Pumping (MGY)
0
5000
10000
15000
20000
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Interpolated IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR



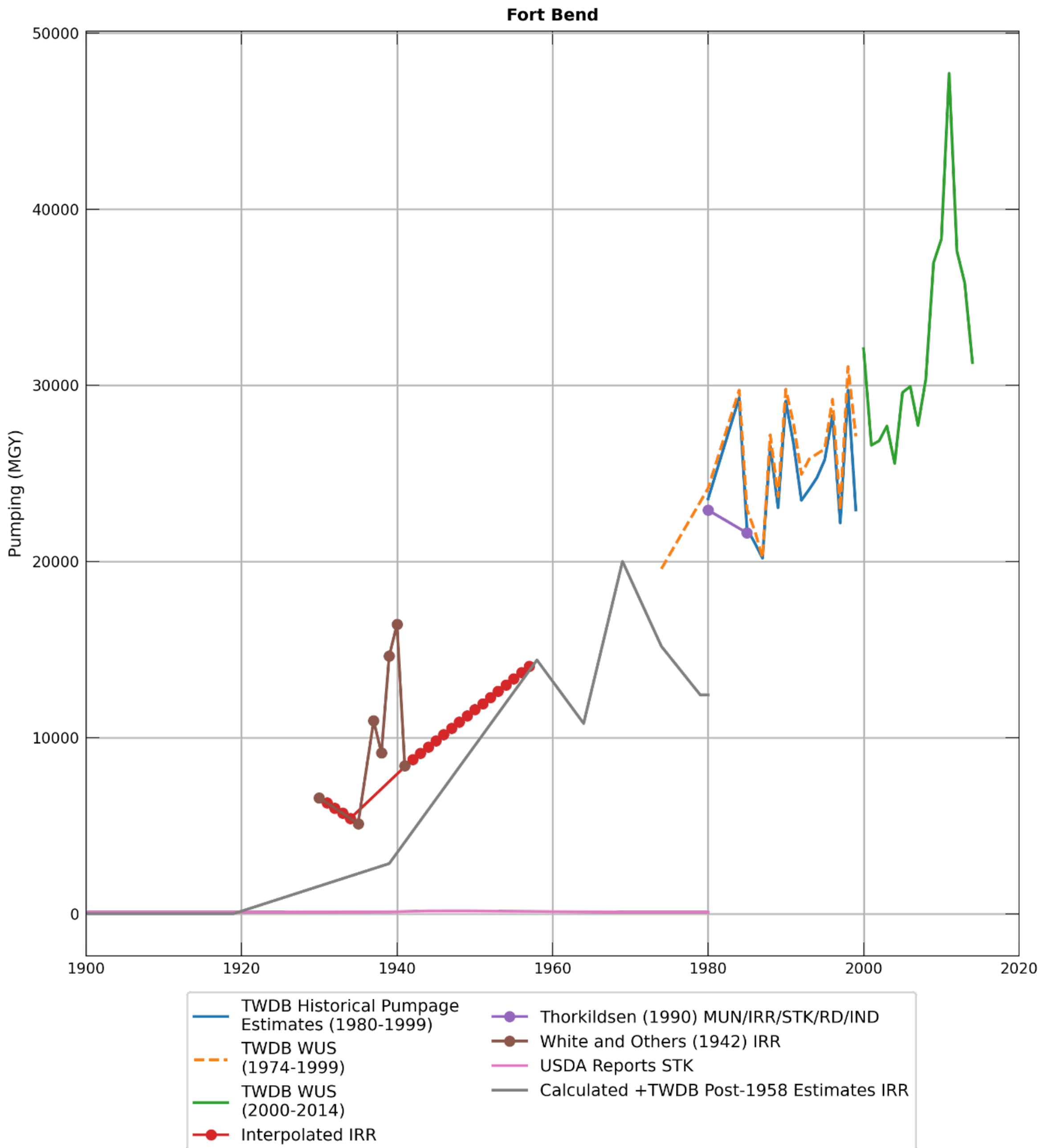
Chambers
Pumping (MGY)
3500
3000
2500
2000
1500
1000
500
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Aronow (1971) MUN/IRR/IND
Interpolated MUN/IRR/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR



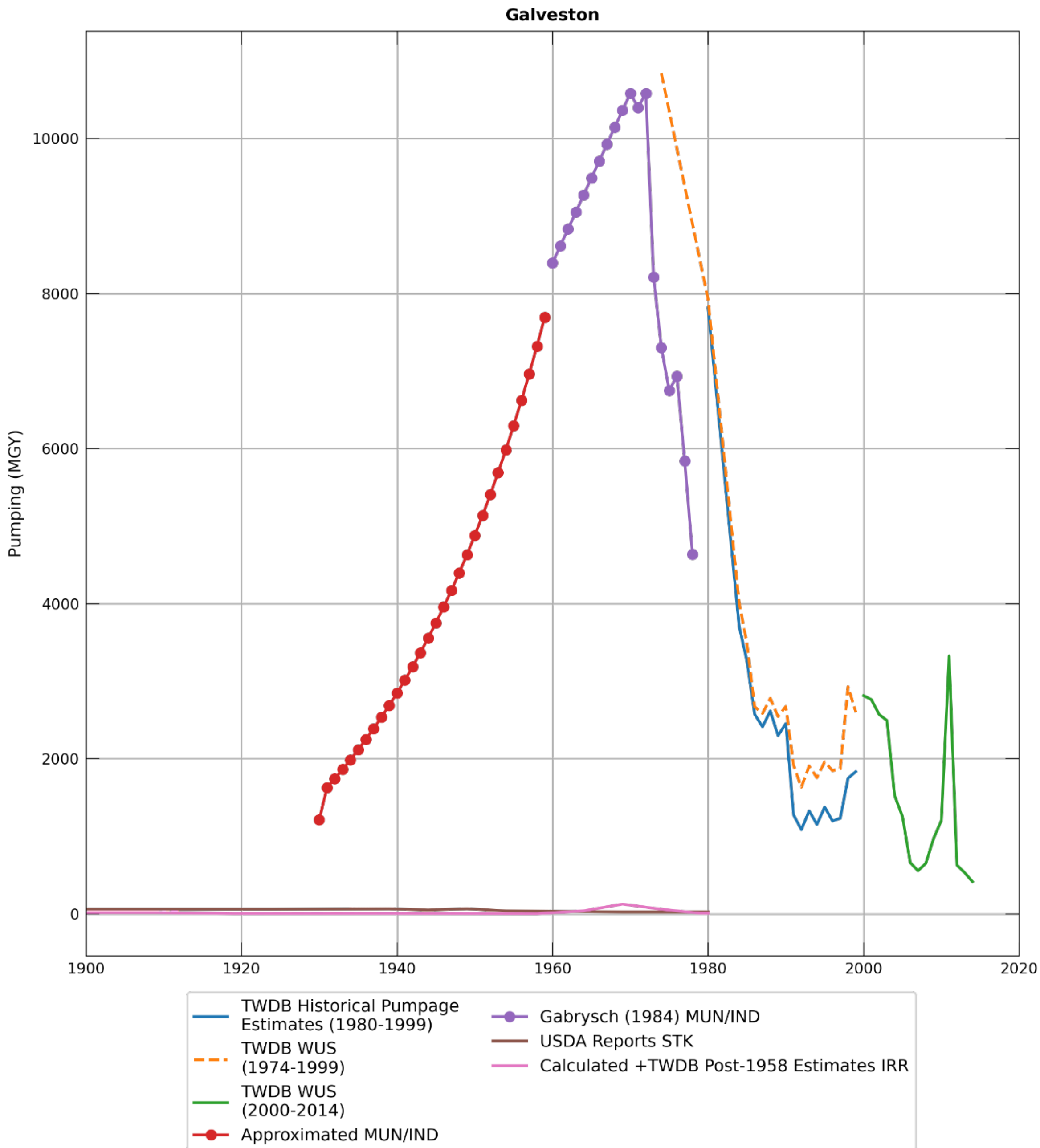
Colorado
Pumping (MGY)
20000
15000
10000
5000
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Loskot (1982) MUN/IRR/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

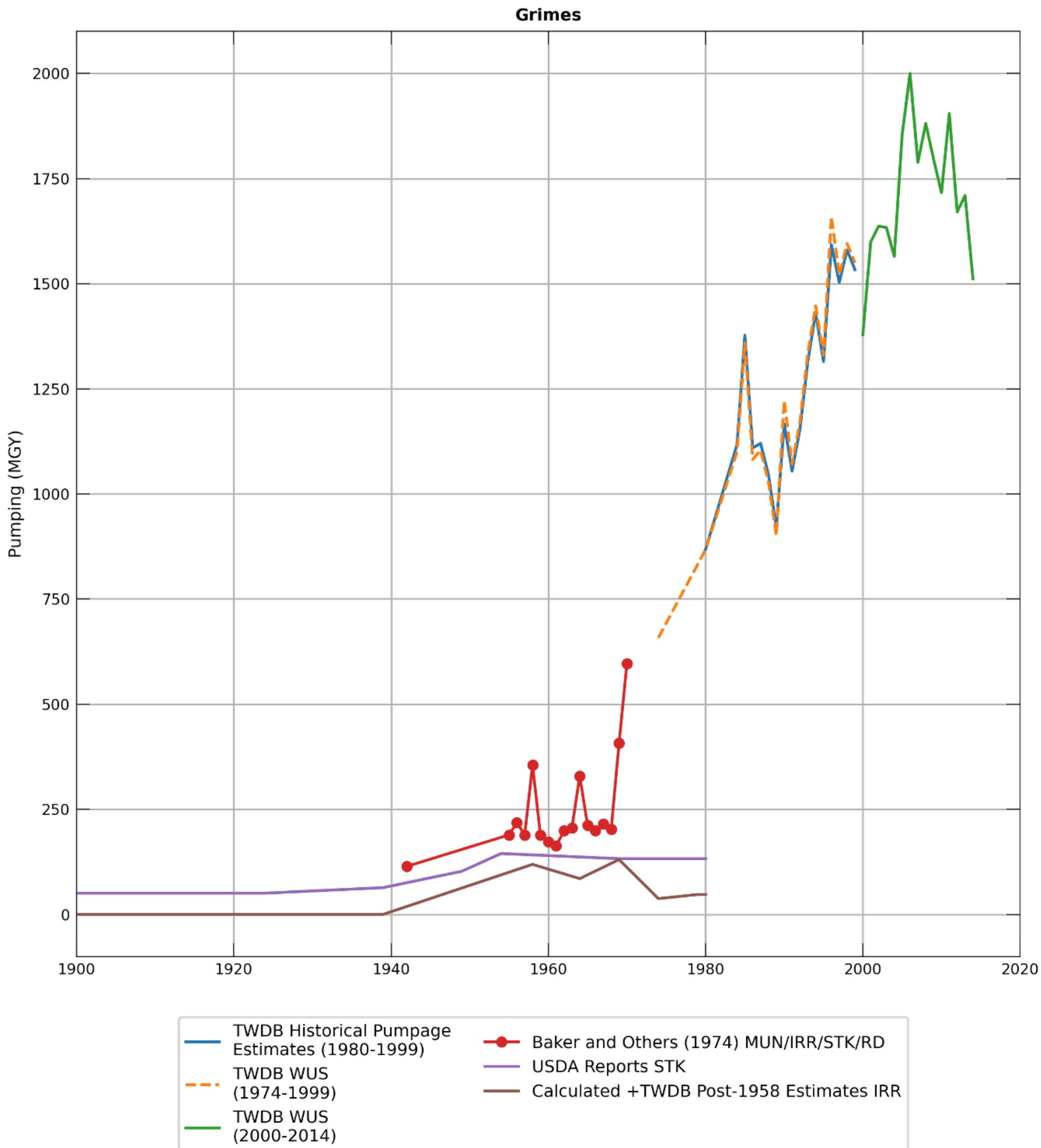


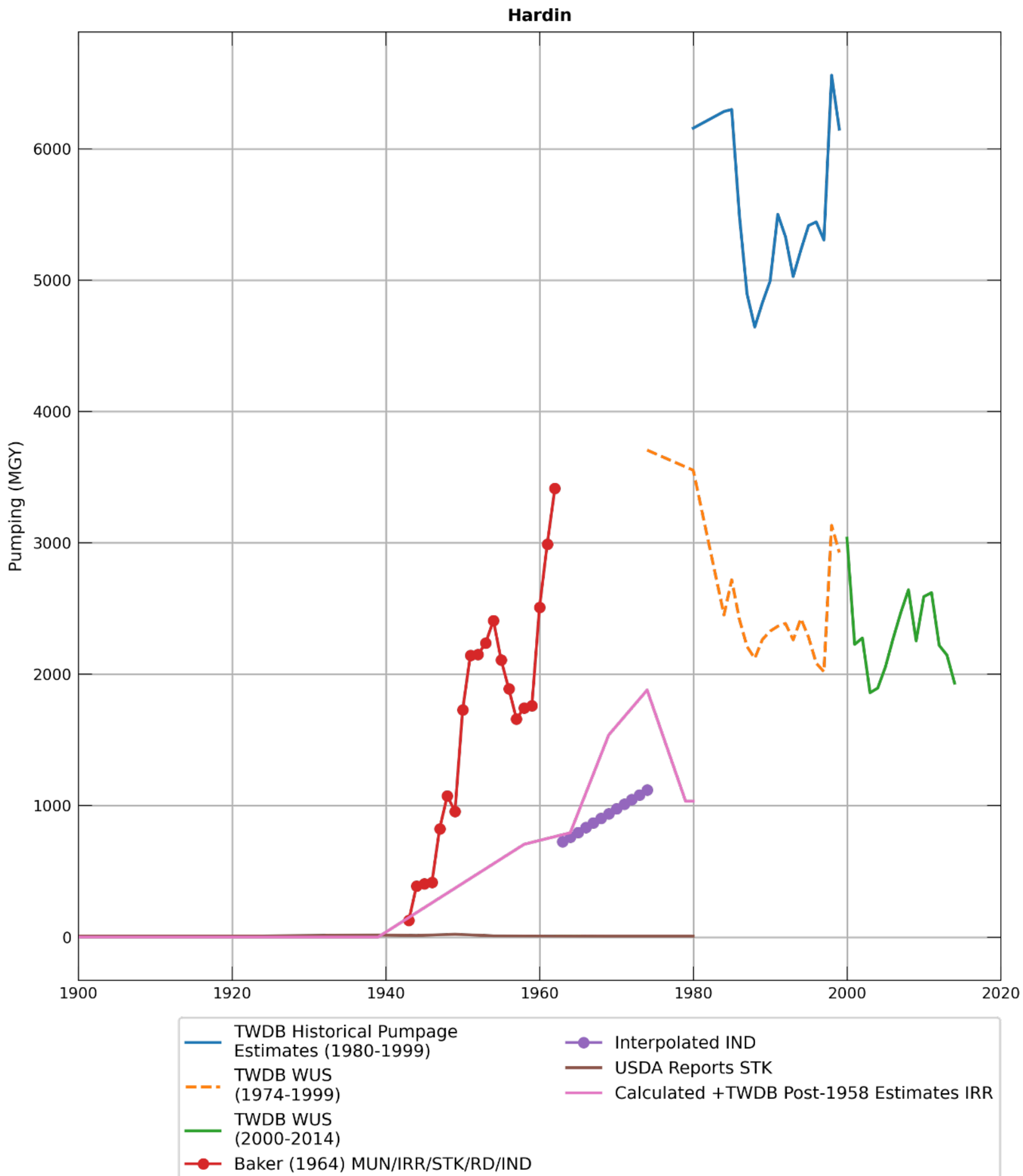
INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS



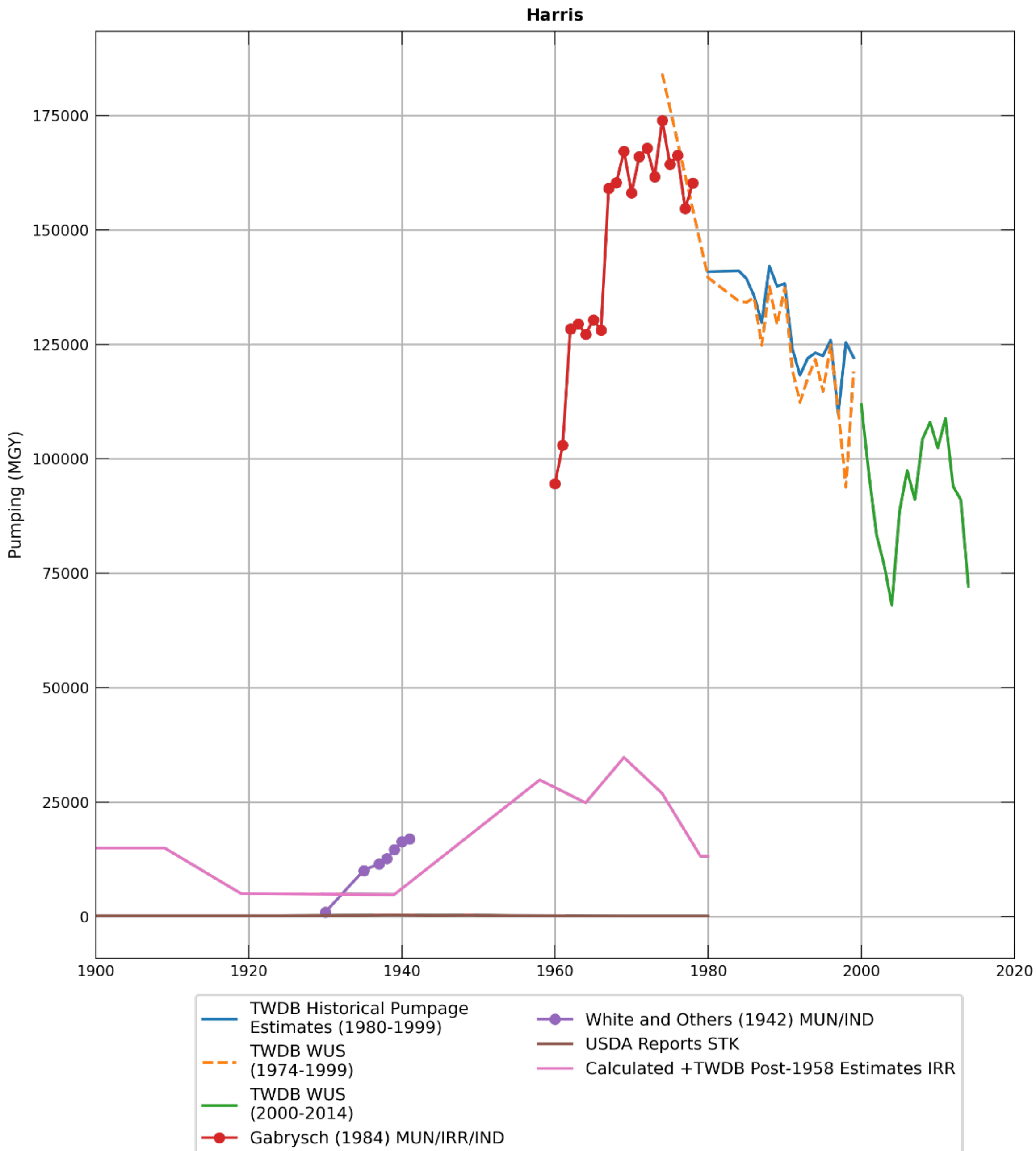
INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS


Galveston
Pumping (MGY)
0
2000
4000
6000
8000
10000
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Approximated MUN/IND
Gabrysch (1984) MUN/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

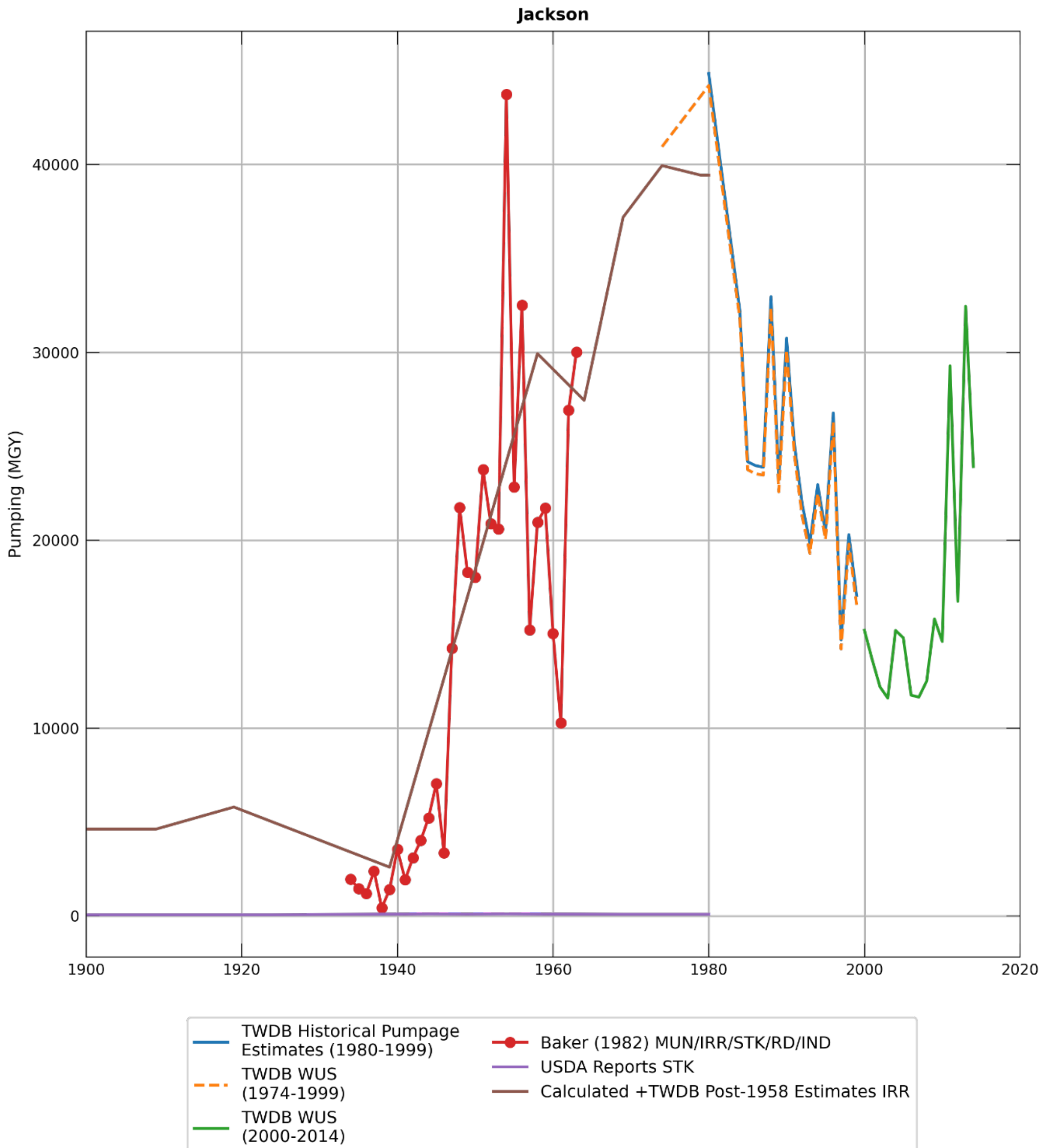

Grimes
Pumping (MGY)
2000
1750
1500
1250
1000
750
500
250
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Baker and Others (1974) MUN/IRR/STK/RD
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

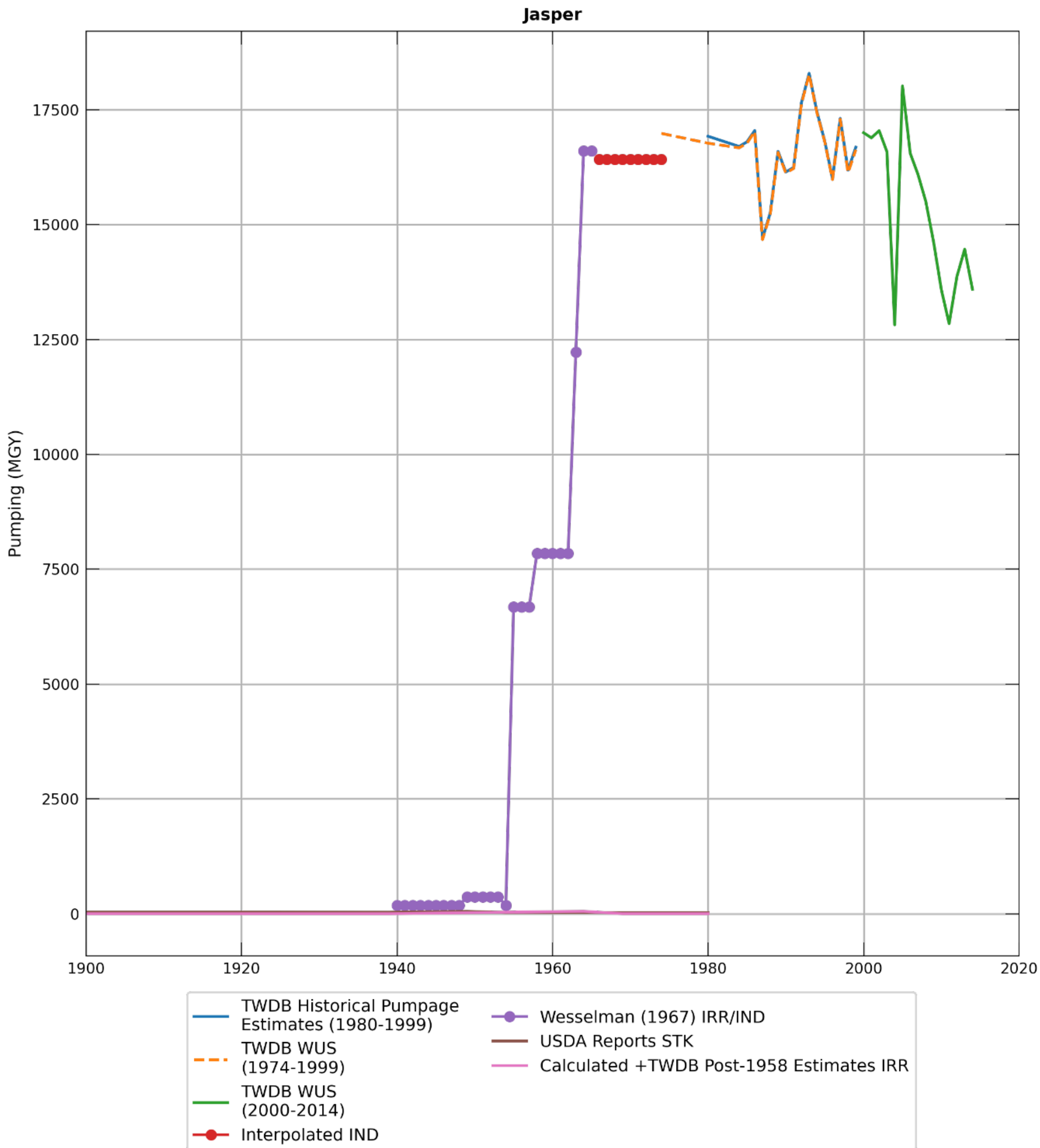


Hardin
Pumping (MGY)
6000
5000
4000
3000
2000
1000
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Baker (1964) MUN/IRR/STK/RD/IND
Interpolated IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

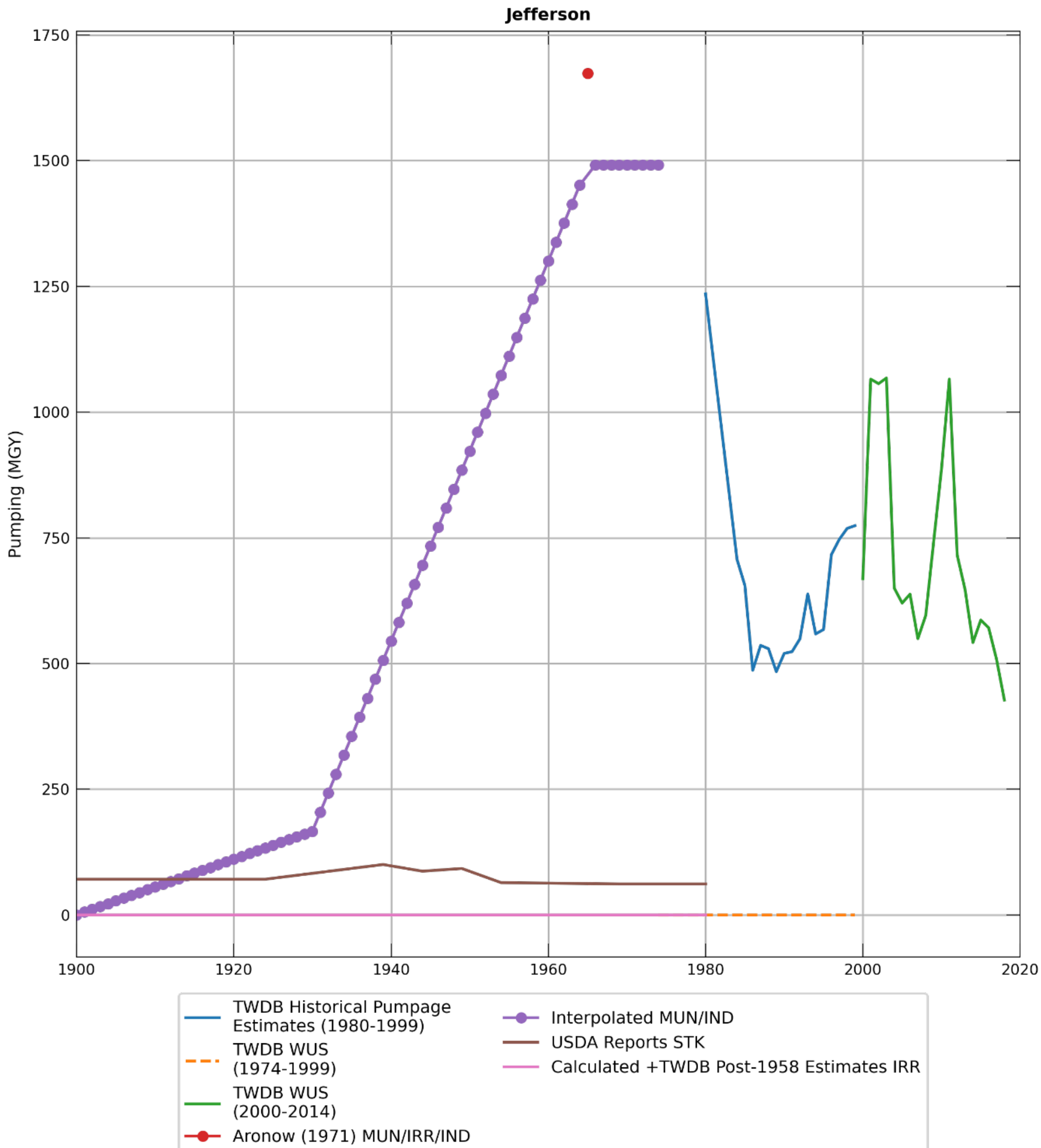


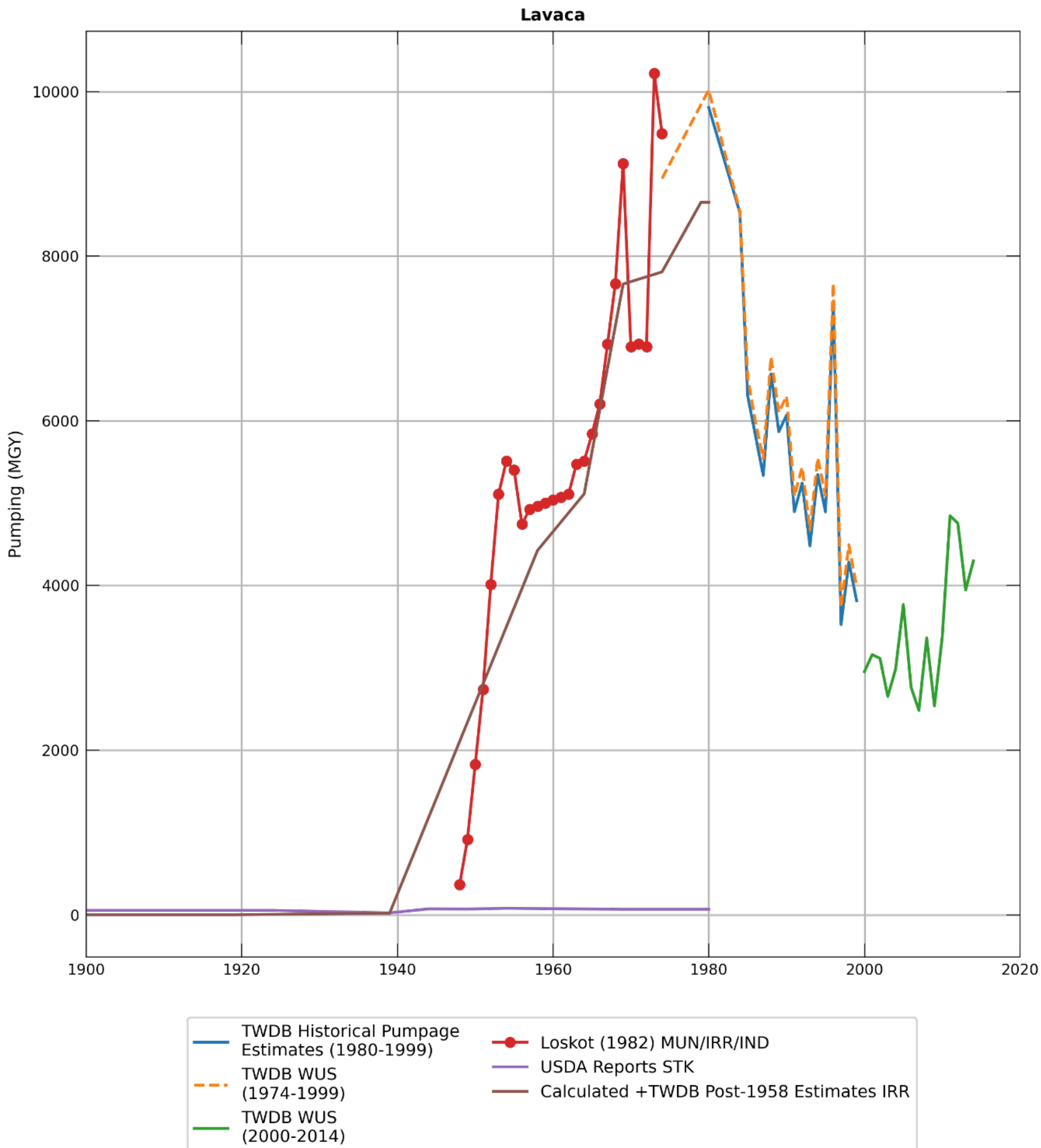
Harris
Pumping (MGY)
175000
150000
125000
100000
75000
50000
25000
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Gabrysch (1984) MUN/IRR/IND
White and Others (1942) MUN/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR


Jackson
Pumping (MGY)
0
10000
20000
30000
40000
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Baker (1982) MUN/IRR/STK/RD/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

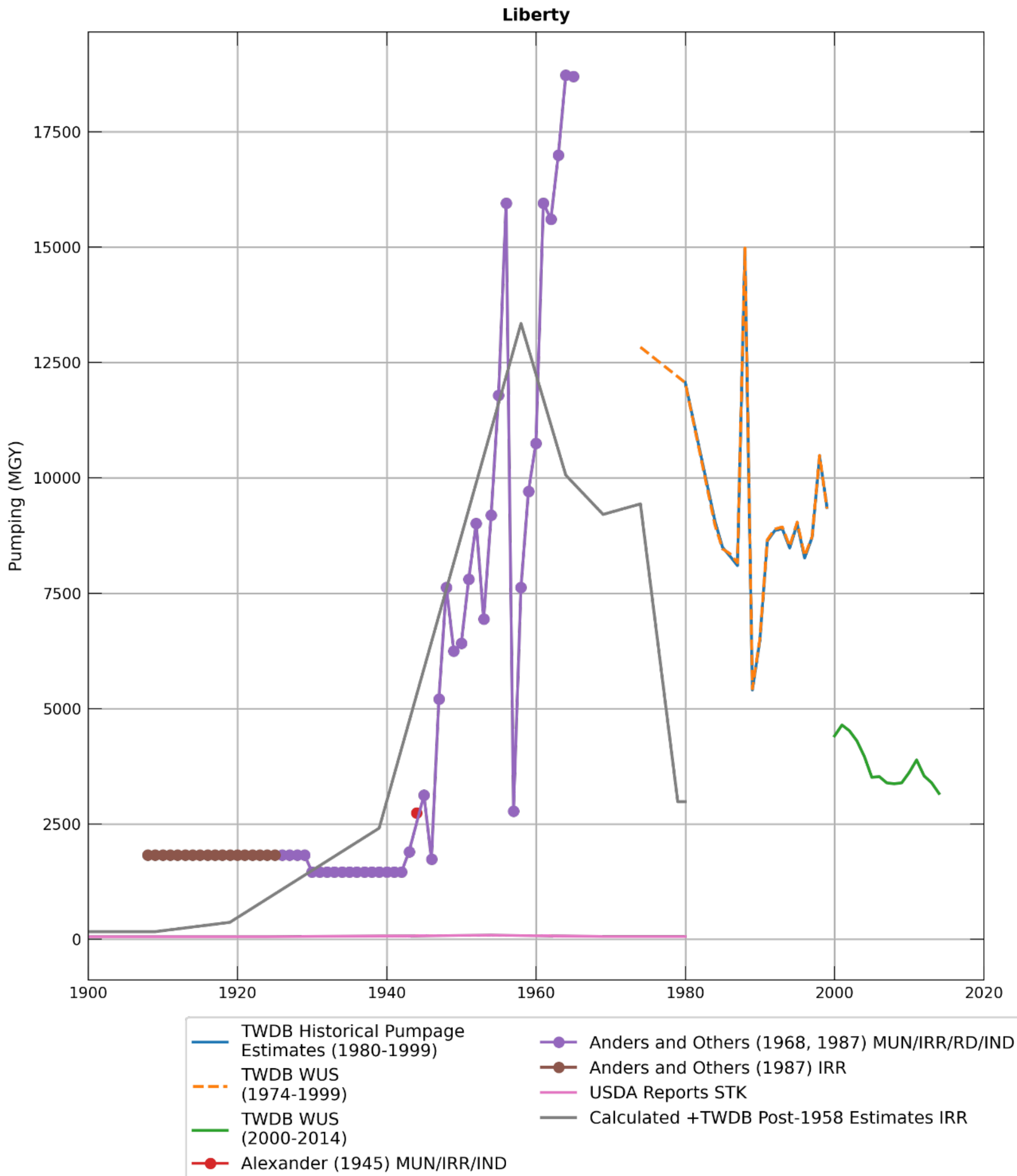


Jasper
Pumping (MGY)
17500
15000
12500
10000
7500
5000
2500
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Interpolated IND
Wesselman (1967) IRR/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

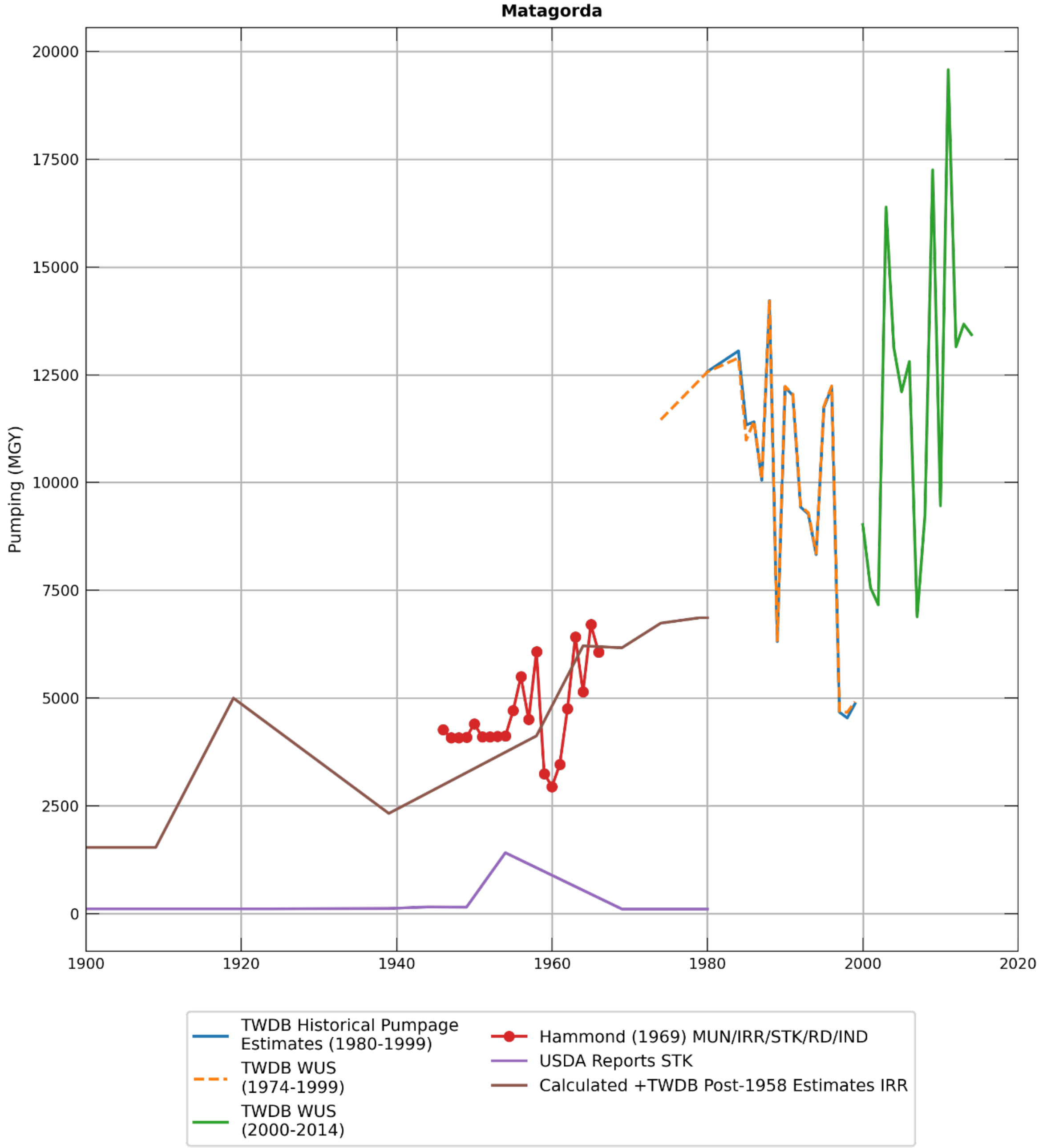

Jefferson
Pumping (MGY)
1750
1500
1250
1000
750
500
250
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Aronow (1971) MUN/IRR/IND
Interpolated MUN/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

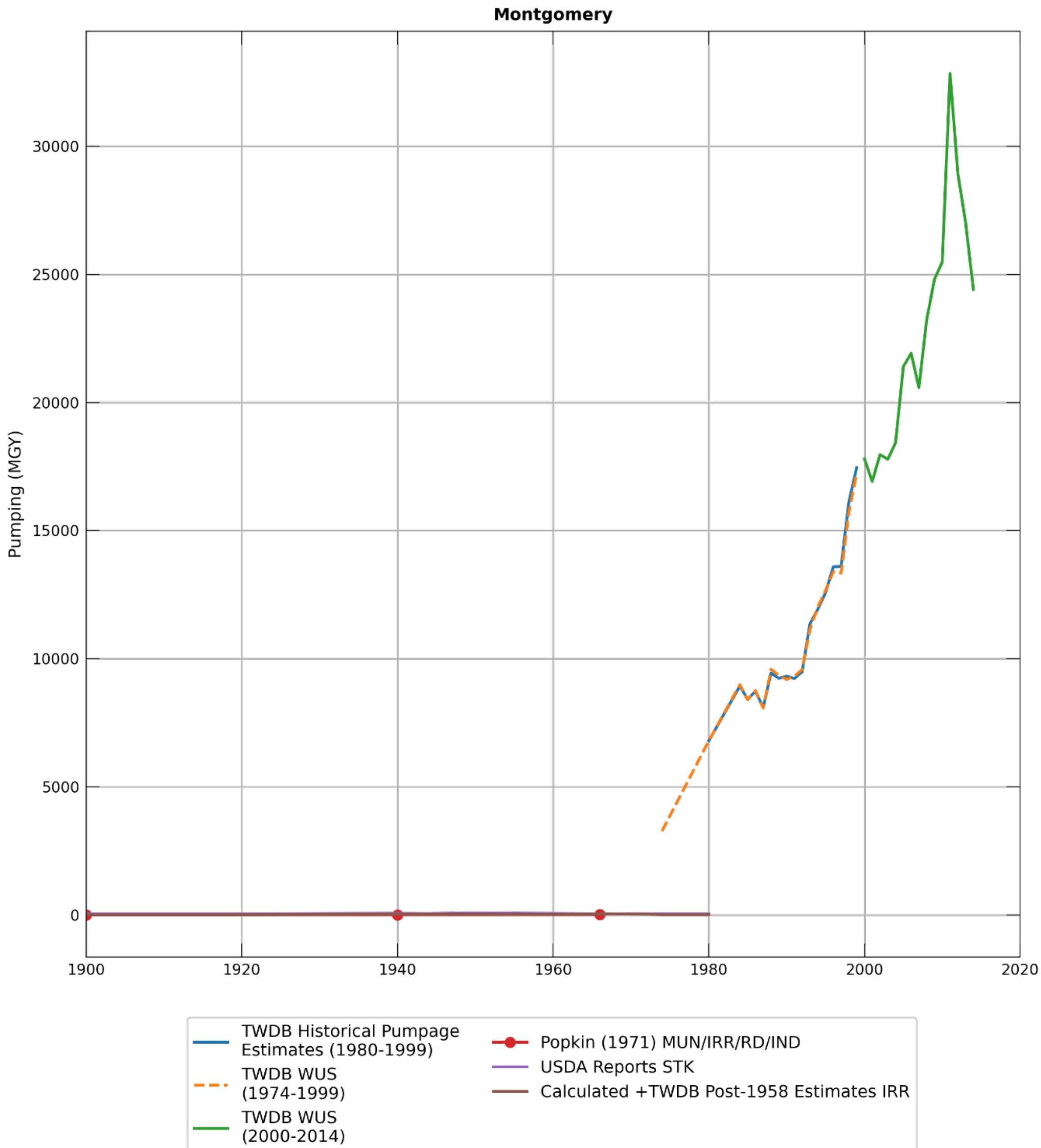


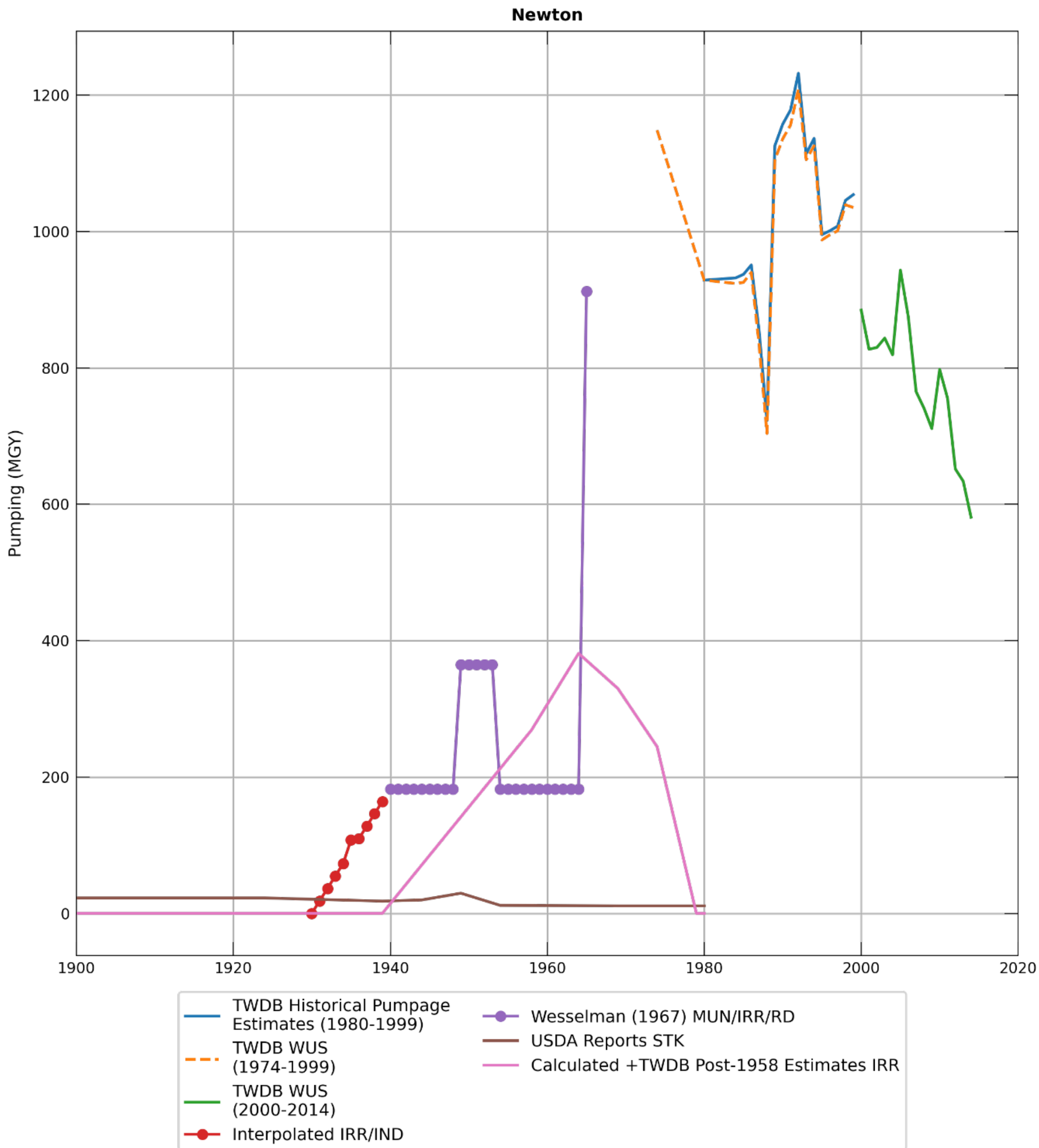
INTERA GEOSCIENCE & ENGINEERING SOLUTIONS

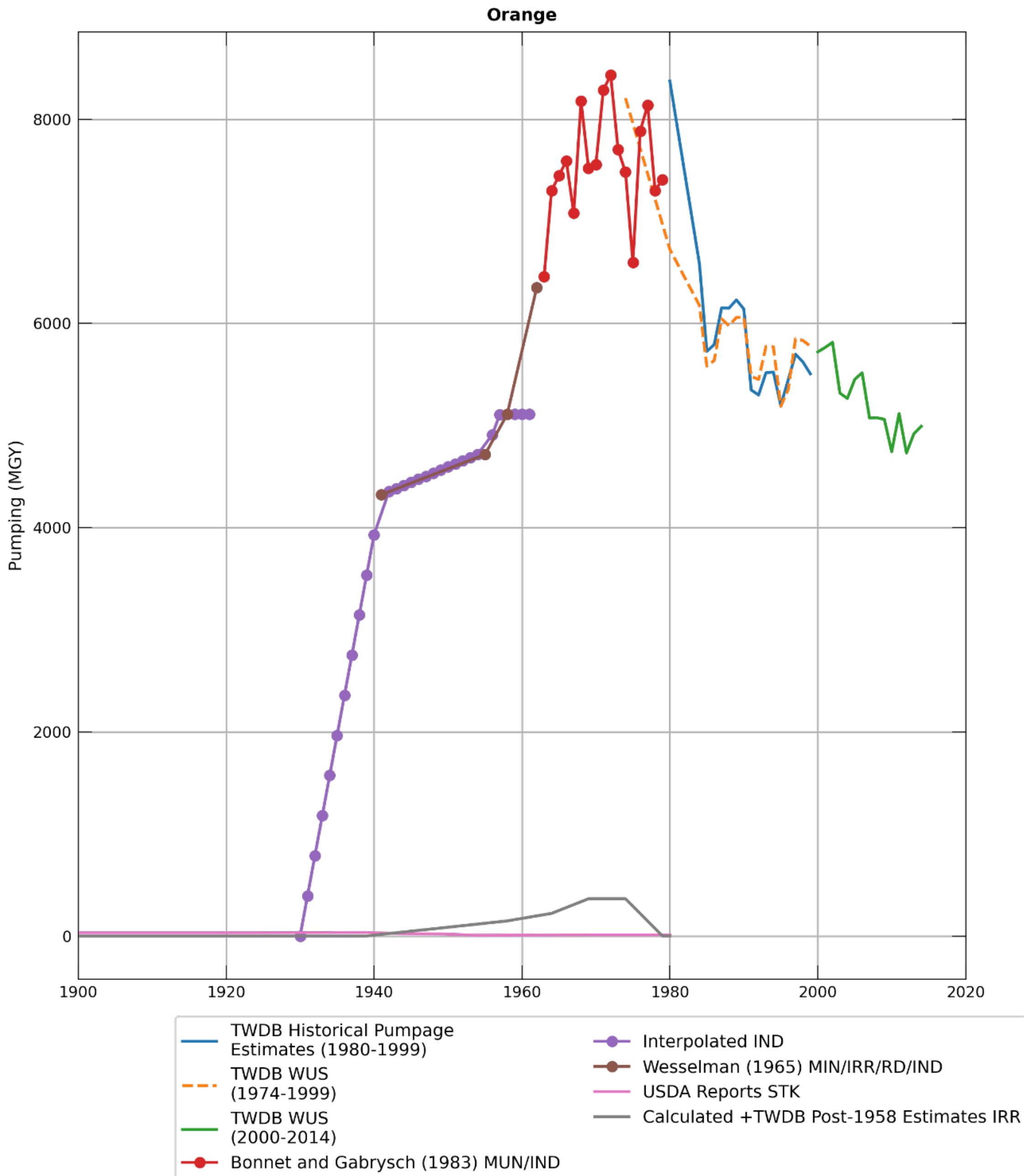


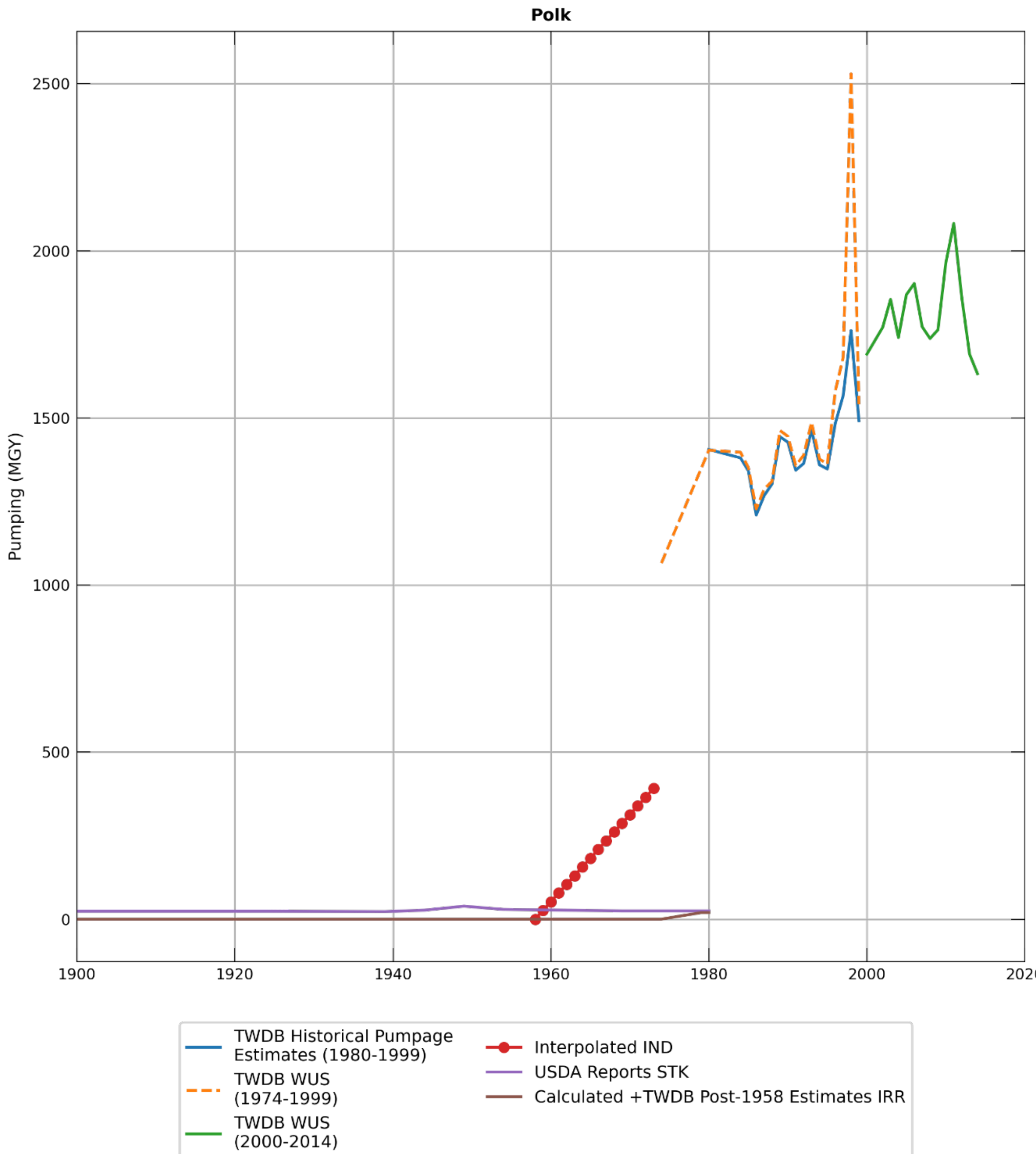
Liberty
Pumping (MGY)
17500
15000
12500
10000
7500
5000
2500
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Alexander (1945) MUN/IRR/IND
Anders and Others (1968, 1987) MUN/IRR/RD/IND
Anders and Others (1987) IRR
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR


Matagorda
Pumping (MGY)
20000
17500
15000
12500
10000
7500
5000
2500
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Hammond (1969) MUN/IRR/STK/RD/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

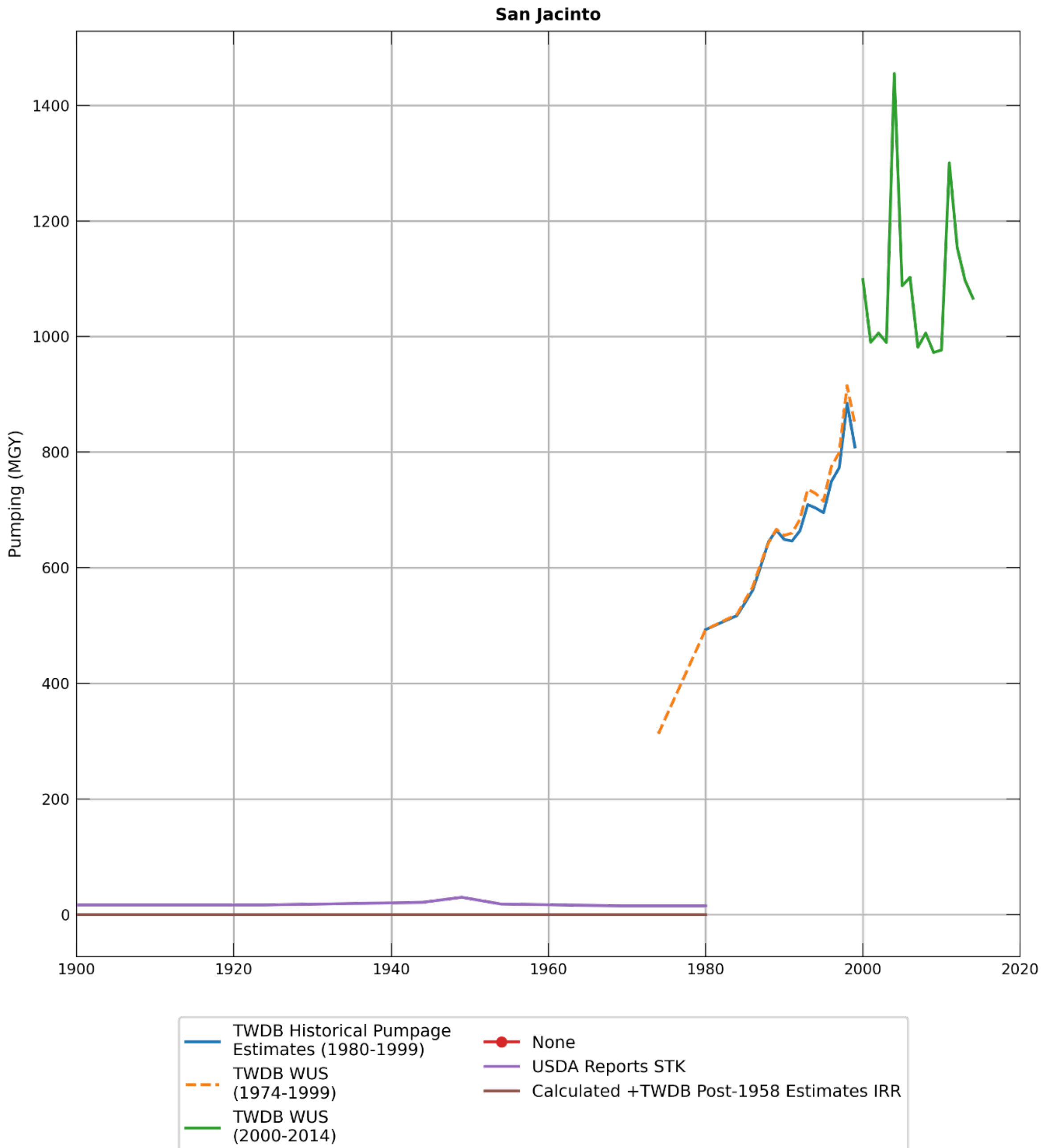

Montgomery
Pumping (MGY)
30000
25000
20000
15000
10000
5000
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Popkin (1971) MUN/IRR/RD/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR


Newton
Pumping (MGY)
0
200
400
600
800
1000
1200
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Interpolated IRR/IND
Wesselman (1967) MUN/IRR/RD
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

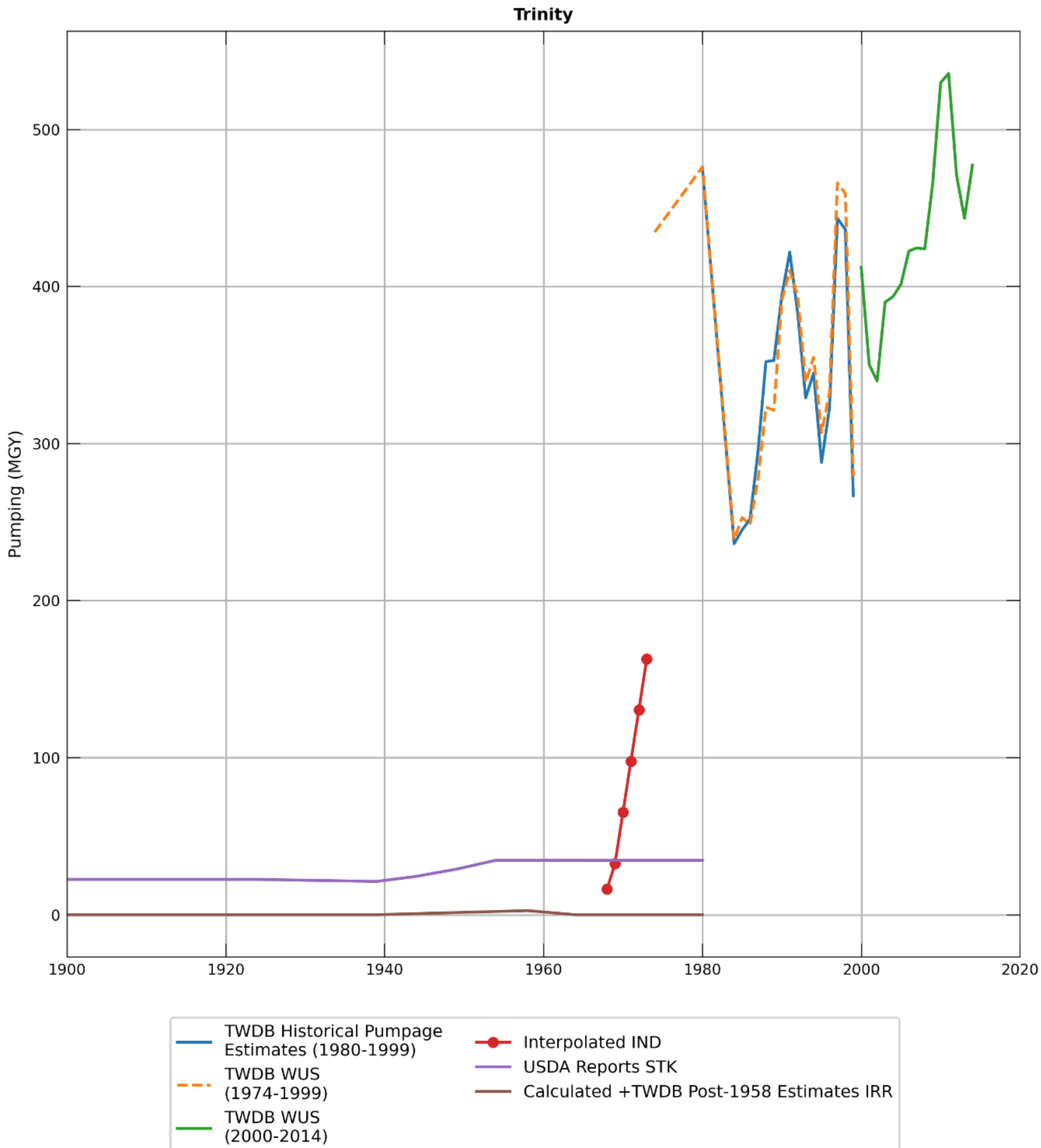

Orange
Pumping (MGY)
8000
6000
4000
2000
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Bonnet and Gabrysch (1983) MUN/IND
Interpolated IND
Wesselman (1965) MIN/IRR/RD/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR



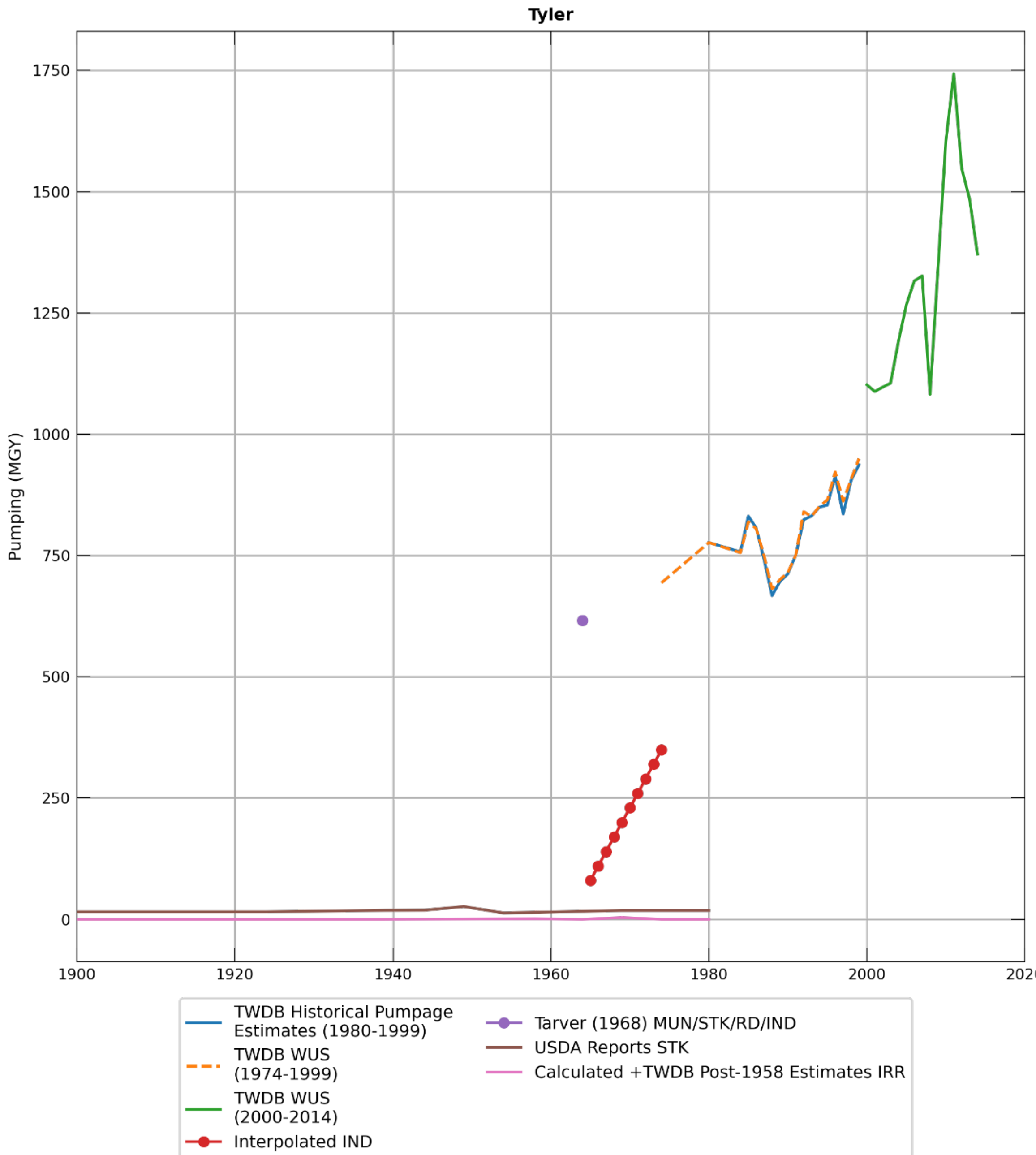
INTERA GEOSCIENCE & ENGINEERING SOLUTIONS

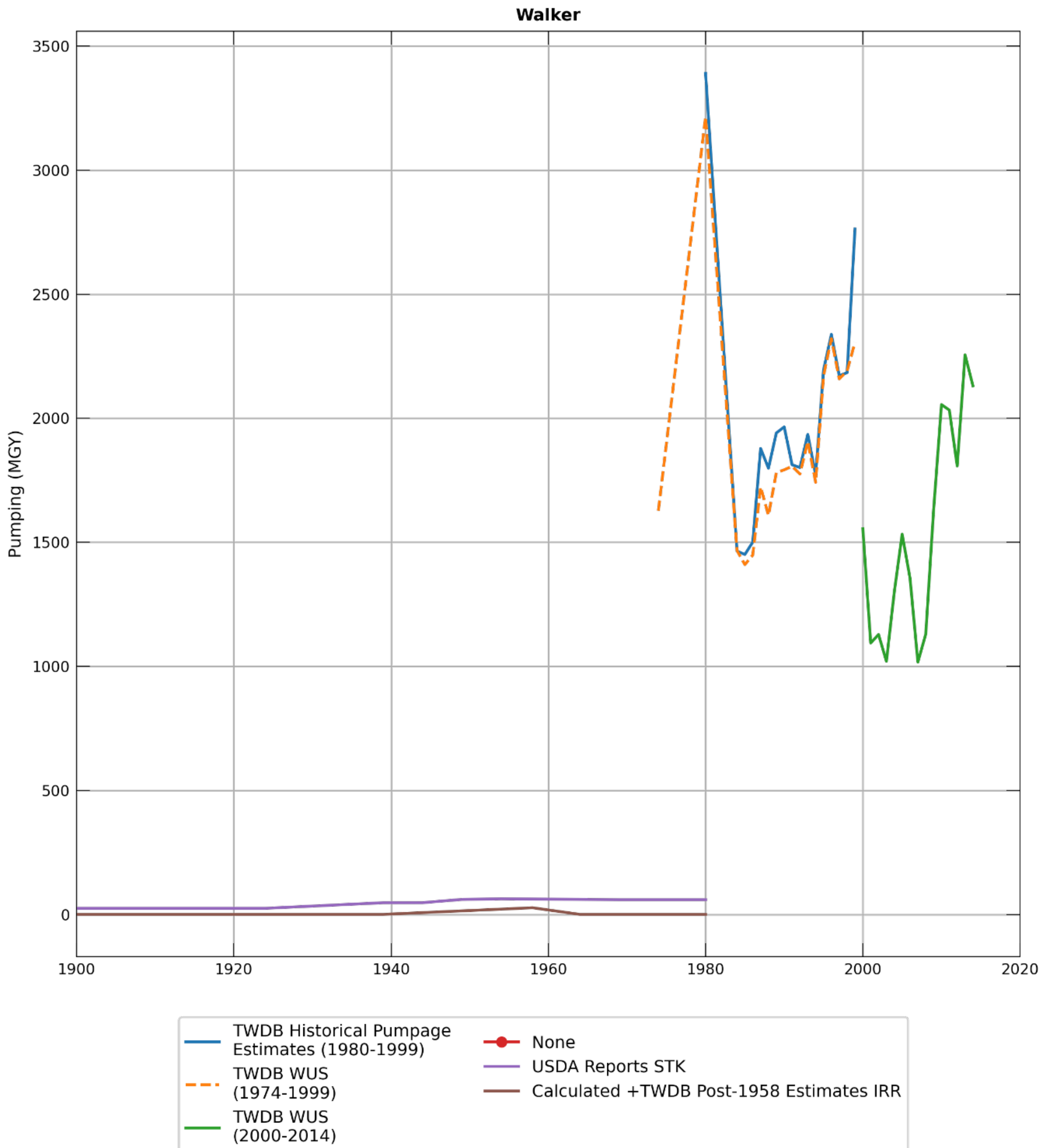


San Jacinto
Pumping (MGY)
1400
1200
1000
800
600
400
200
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
None
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

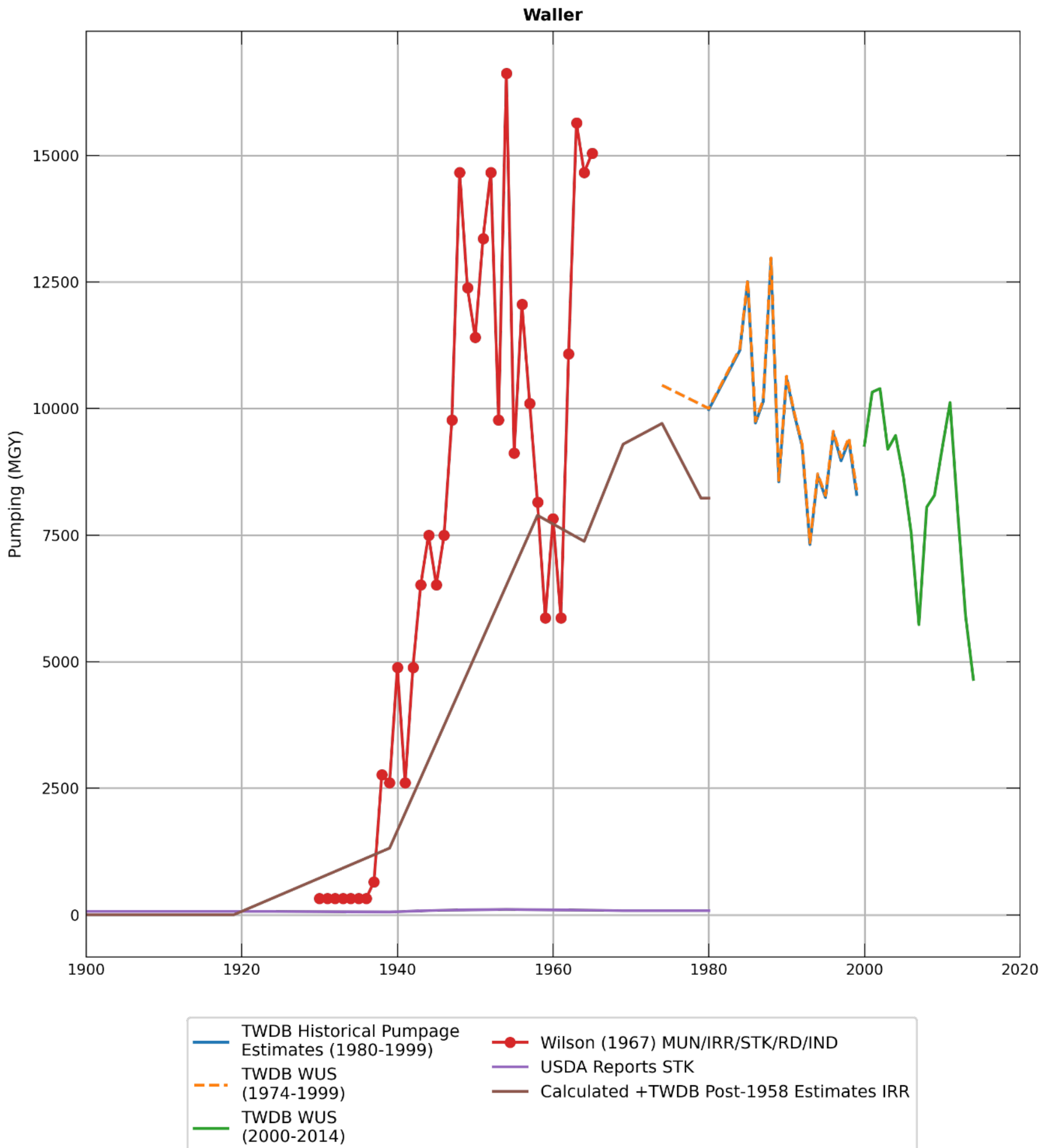


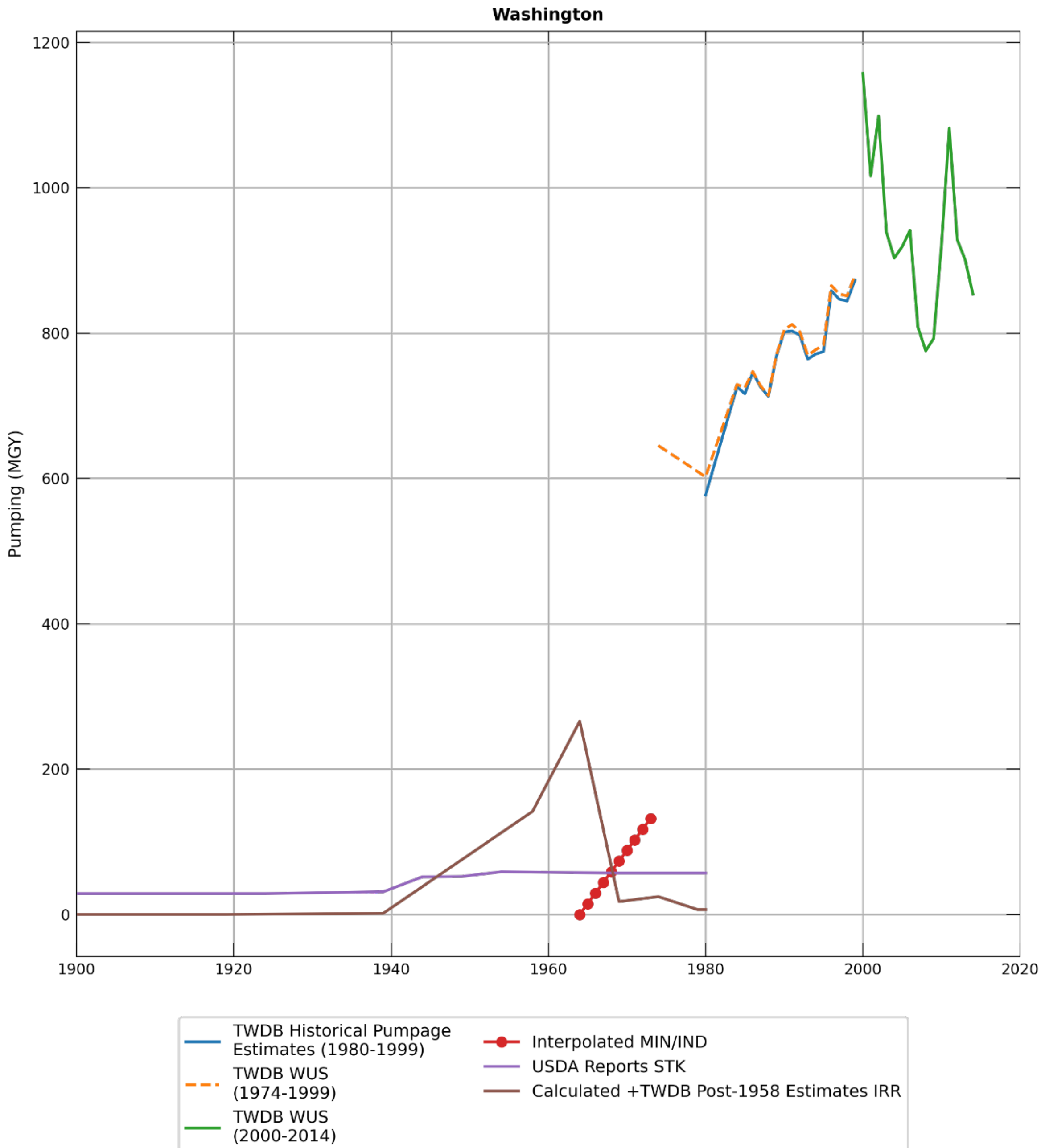
INTERA GEOSCIENCE & ENGINEERING SOLUTIONS

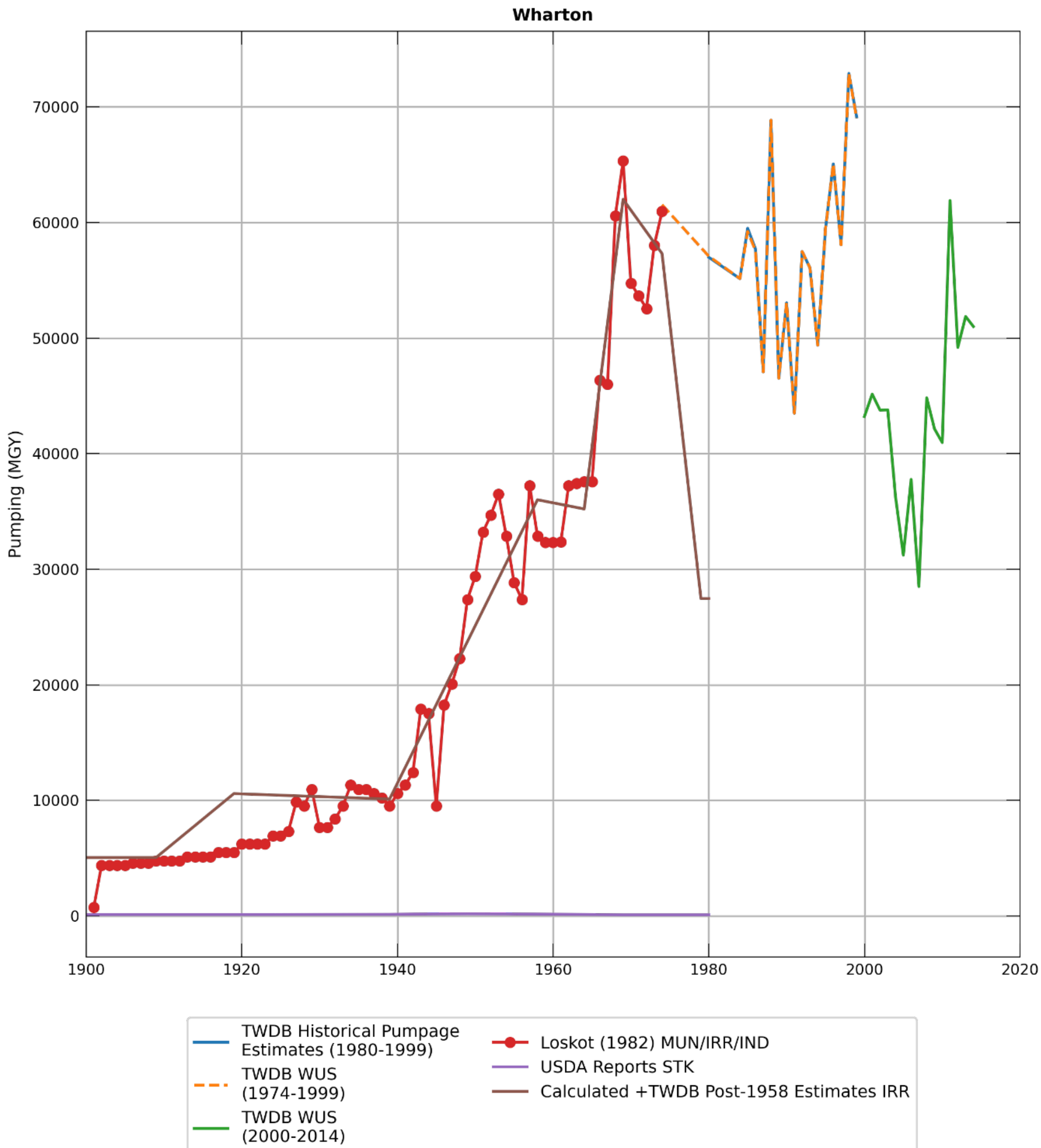

Tyler
Pumping (MGY)
1750
1500
1250
1000
750
500
250
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Interpolated IND
Tarver (1968) MUN/STK/RD/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR



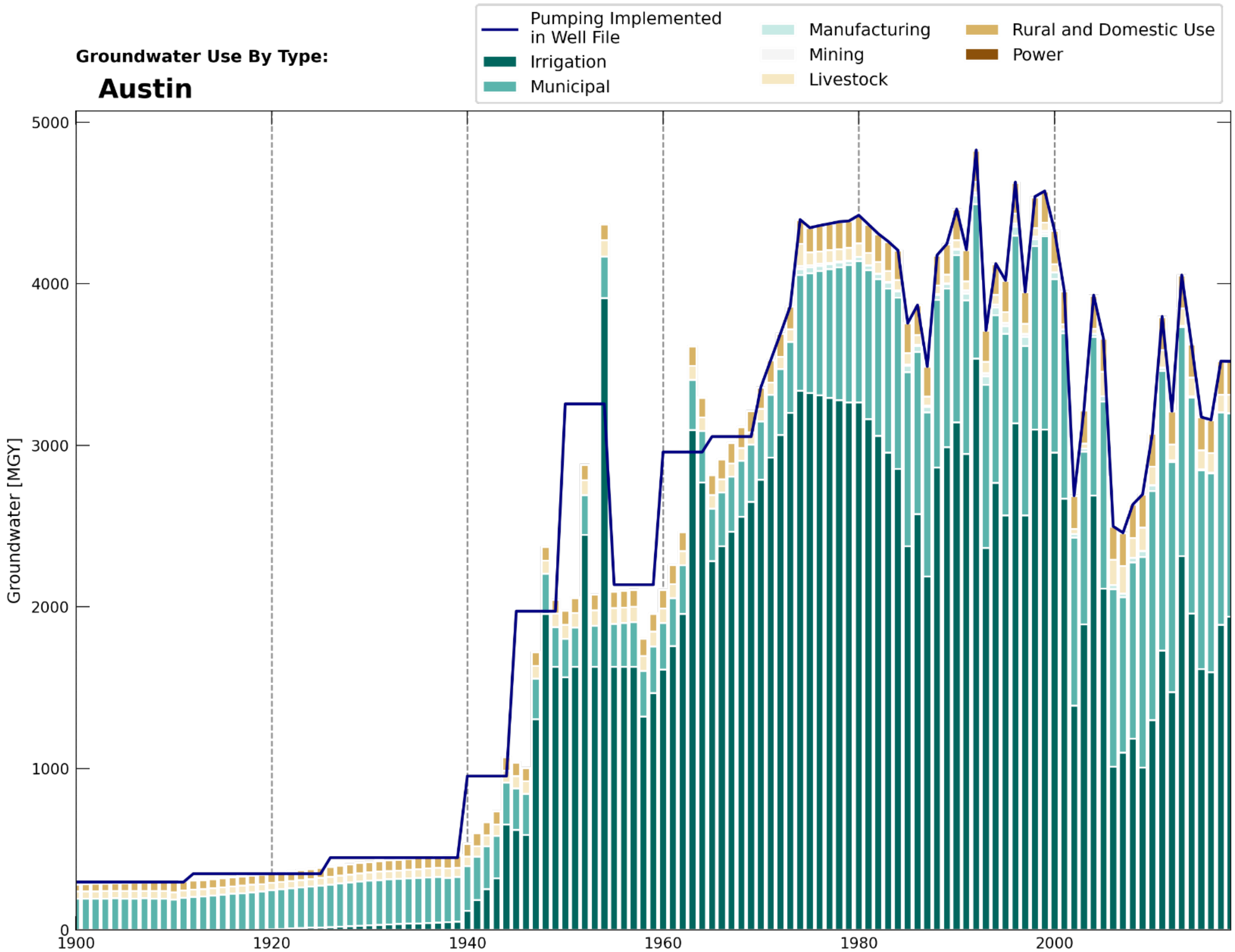
Walker
Pumping (MGY)
3500
3000
2500
2000
1500
1000
500
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
None
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR


Waller
Pumping (MGY)
15000
12500
10000
7500
5000
2500
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Wilson (1967) MUN/IRR/STK/RD/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

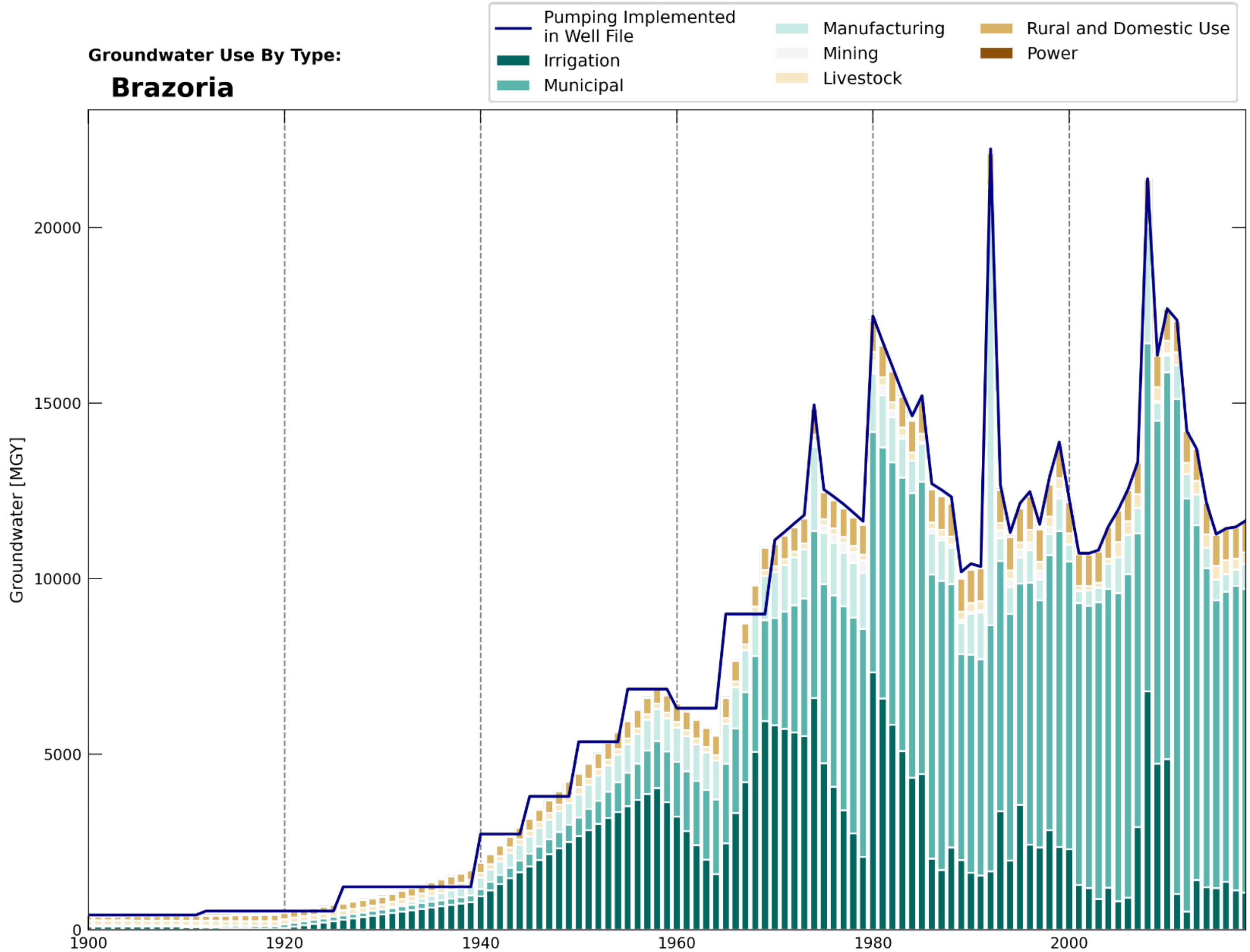

Washington
Pumping (MGY)
1200
1000
800
600
400
200
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Interpolated MIN/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR


Wharton
Pumping (MGY)
70000
60000
50000
40000
30000
20000
10000
0
1900
1920
1940
1960
1980
2000
2020
TWDB Historical Pumpage Estimates (1980-1999)
TWDB WUS (1974-1999)
TWDB WUS (2000-2014)
Loskot (1982) MUN/IRR/IND
USDA Reports STK
Calculated +TWDB Post-1958 Estimates IRR

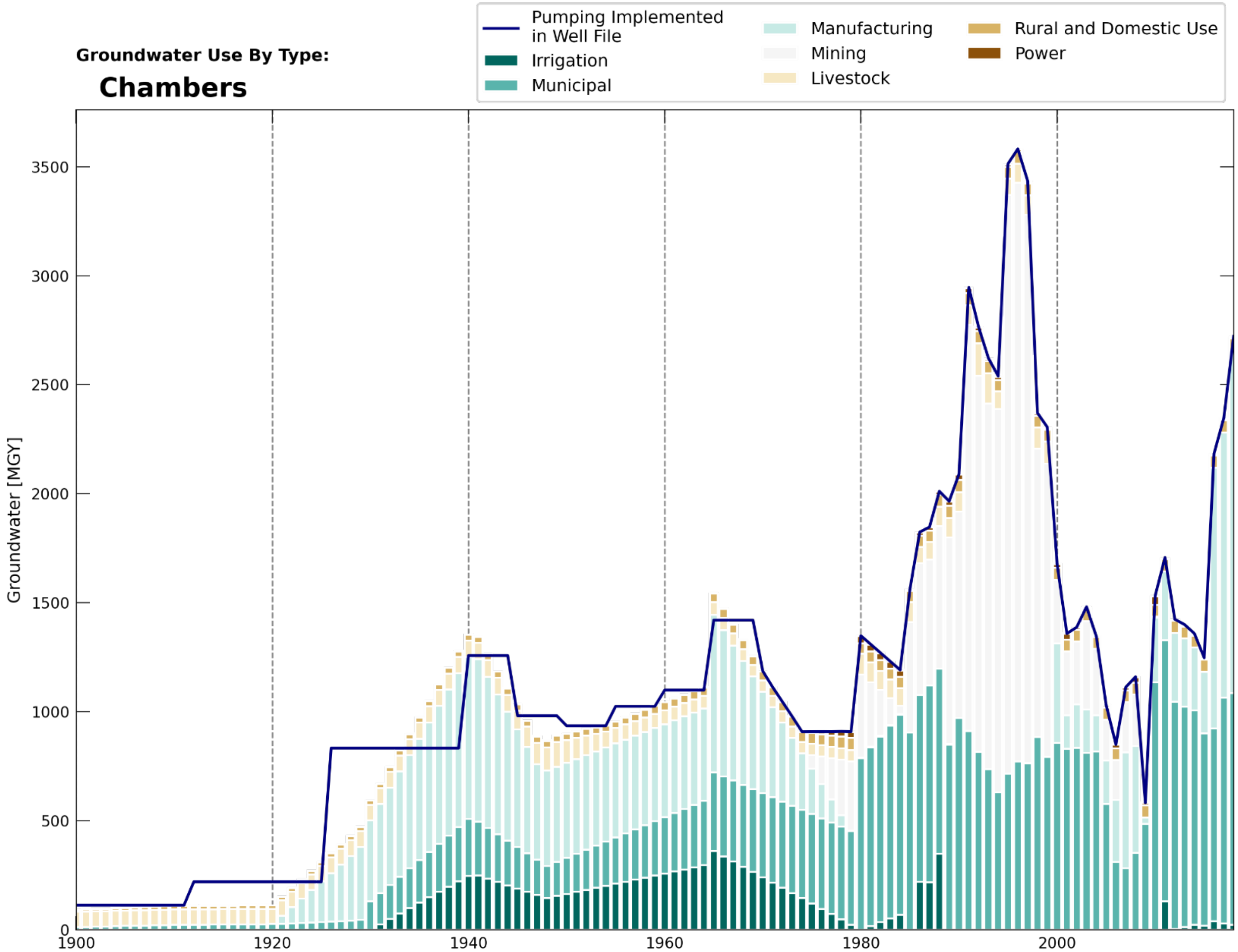
APPENDIX B:
COUNTY PUMPING ESTIMATES BY USE TYPE FROM 1900 TO 2018



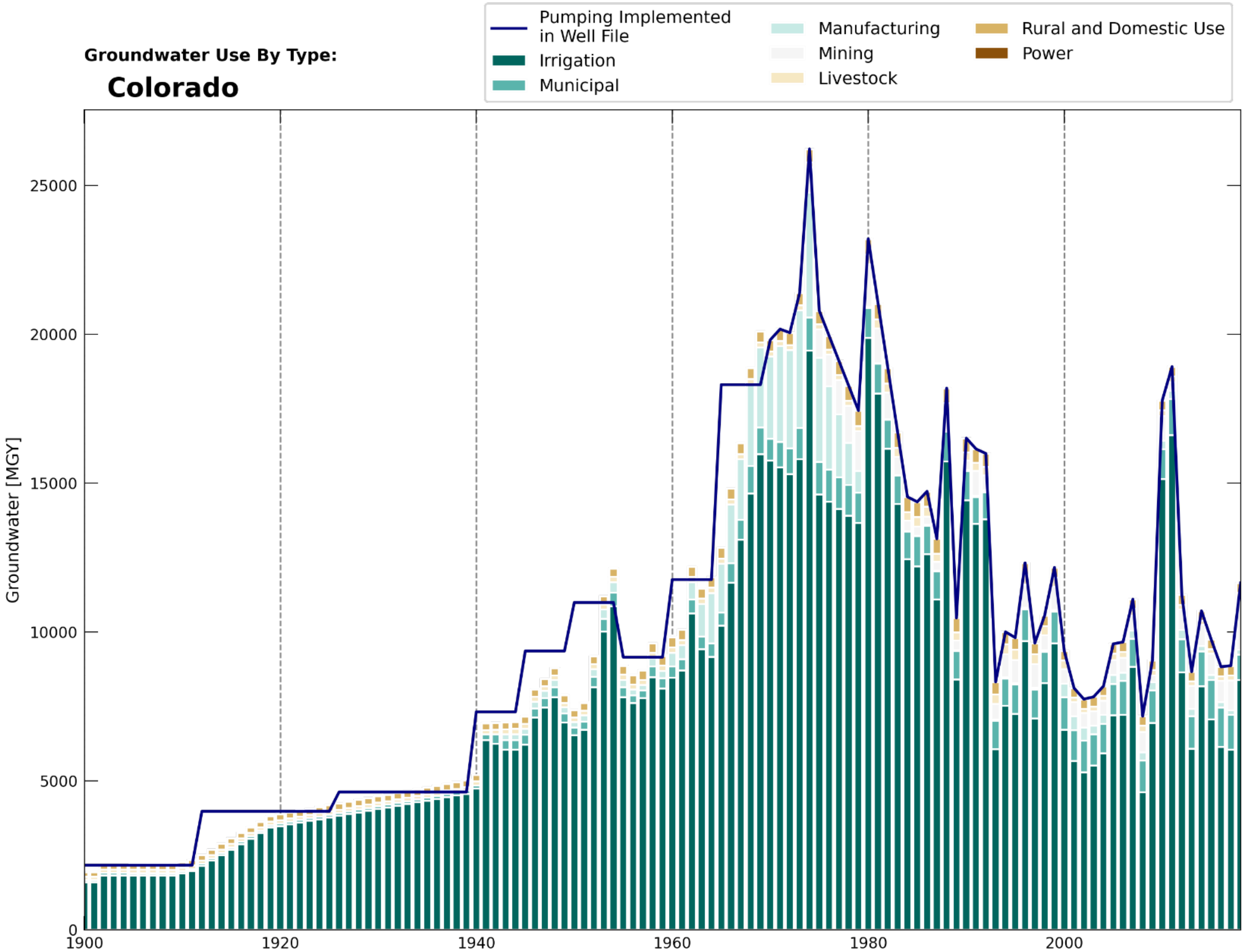
Groundwater Use By Type:
Austin
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
5000
4000
3000
2000
1000
0
Groundwater [MGY]
1900
1920
1940
1960
1980
2000



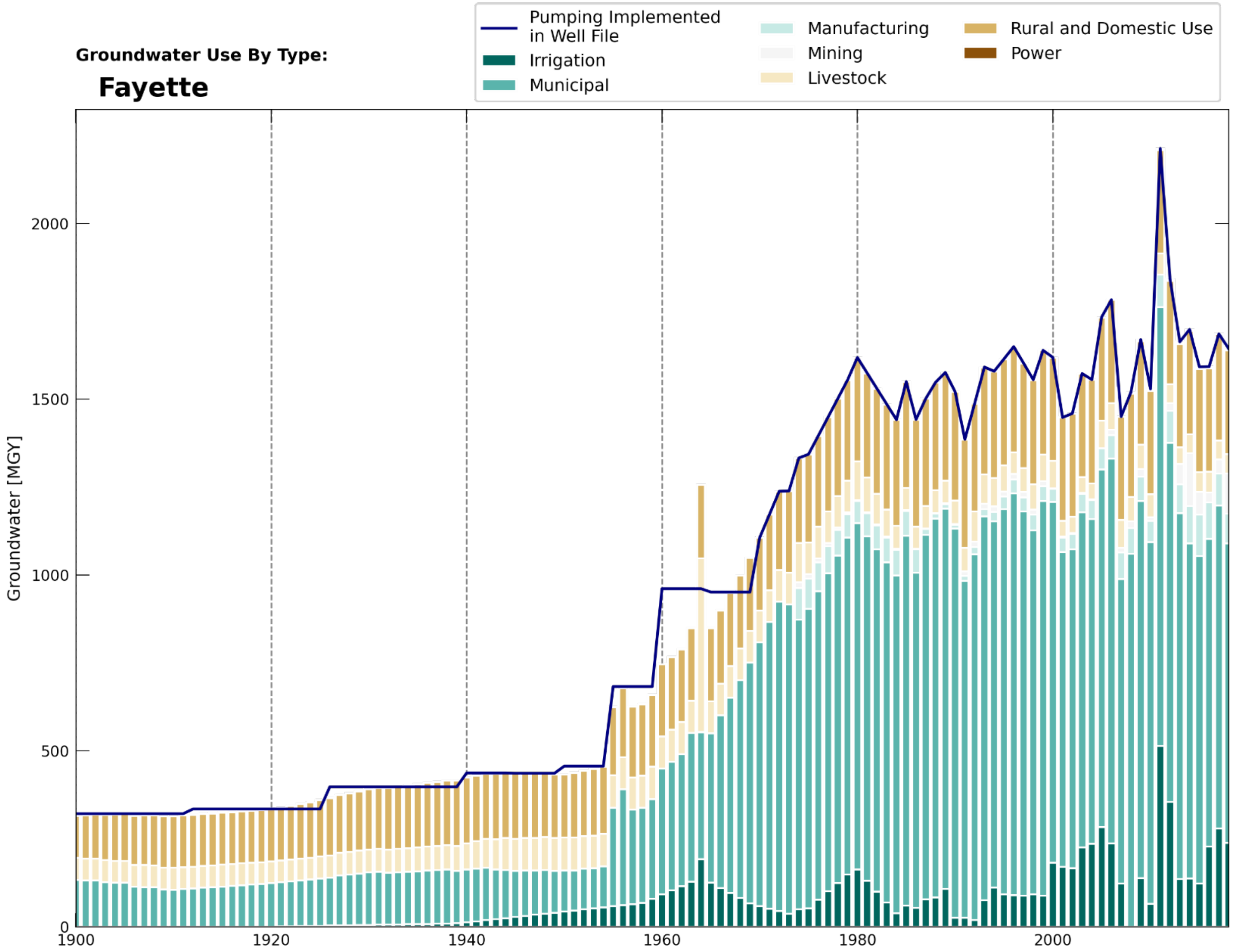
GEOSCIENCE & ENGINEERING SOLUTIONS

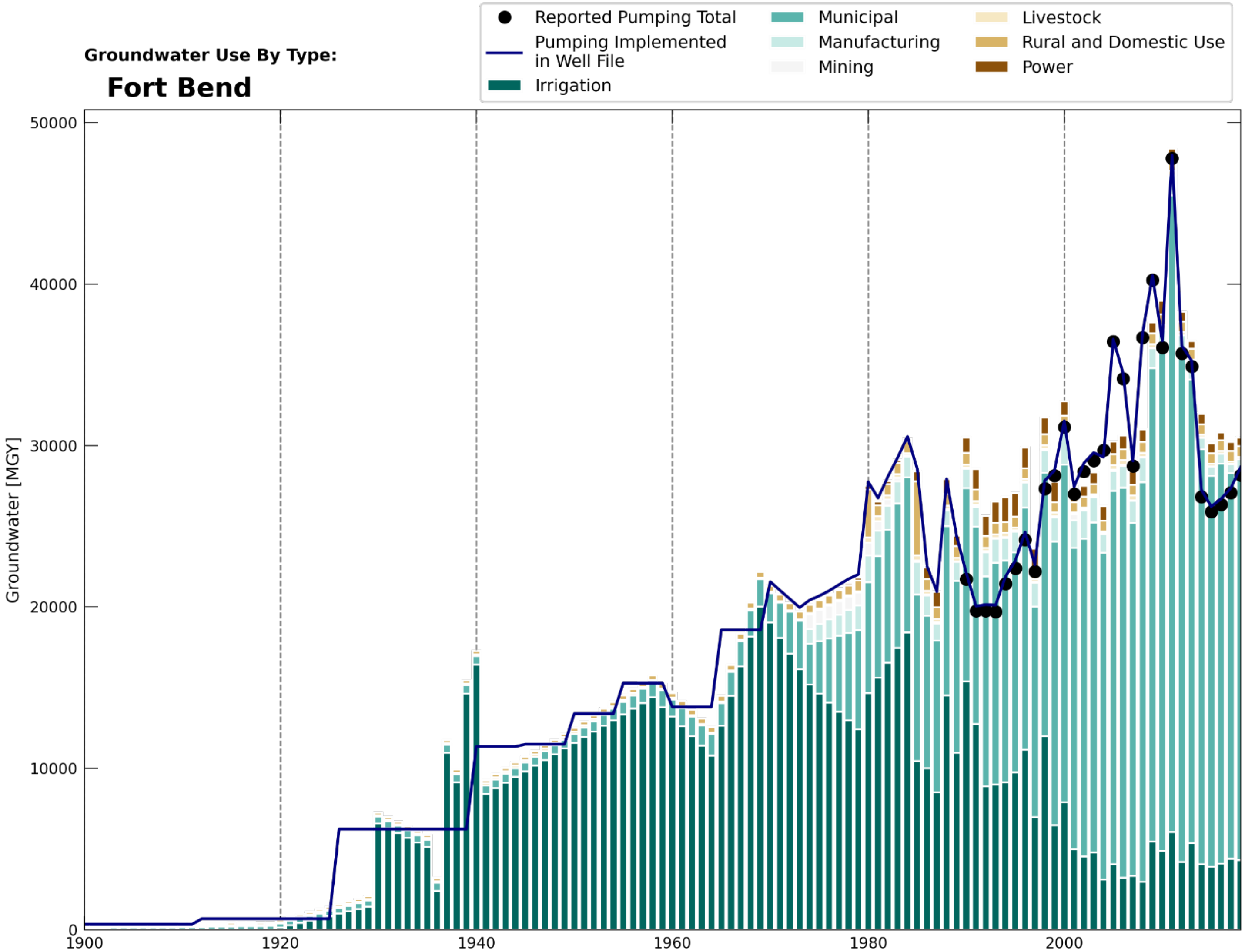


INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

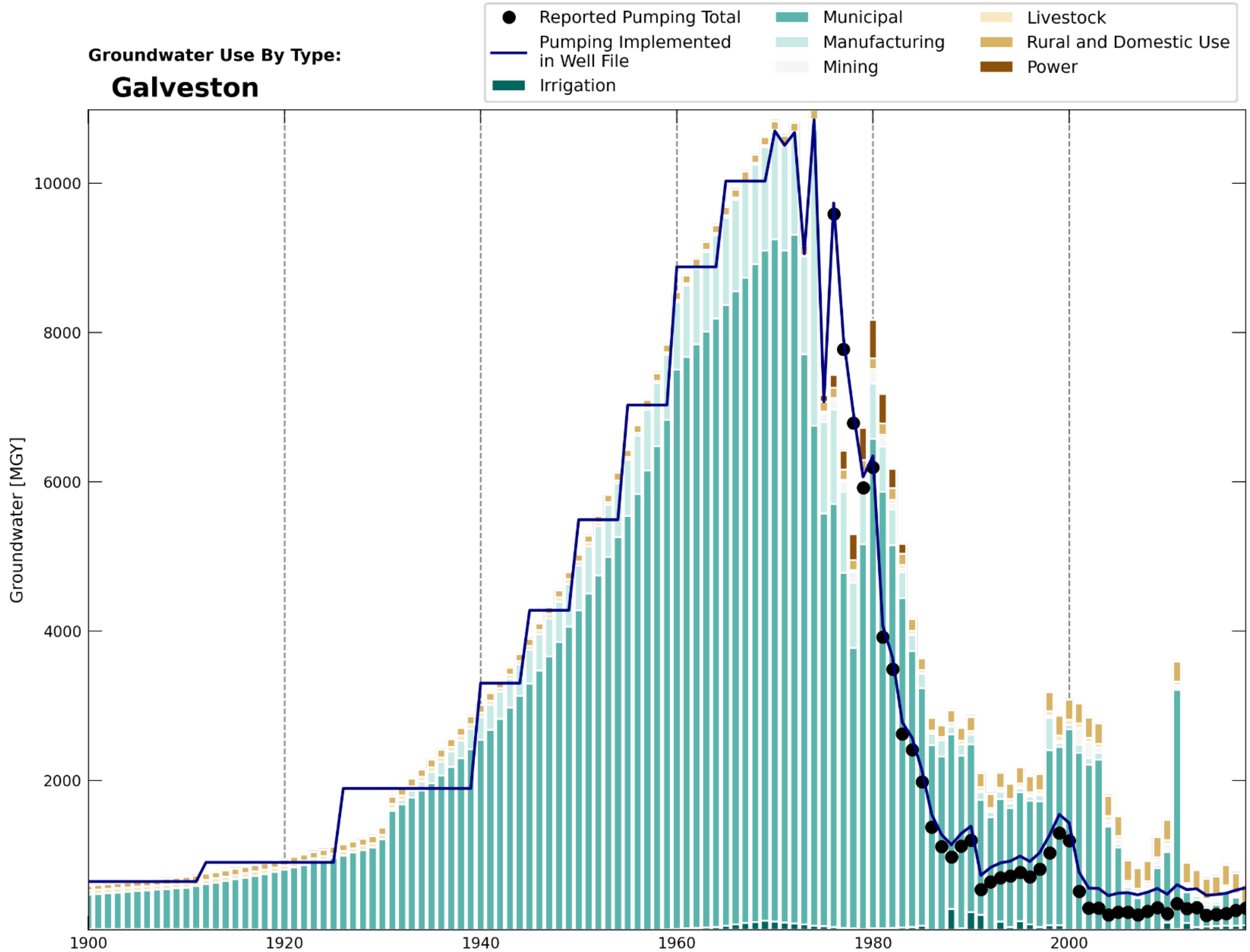


INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

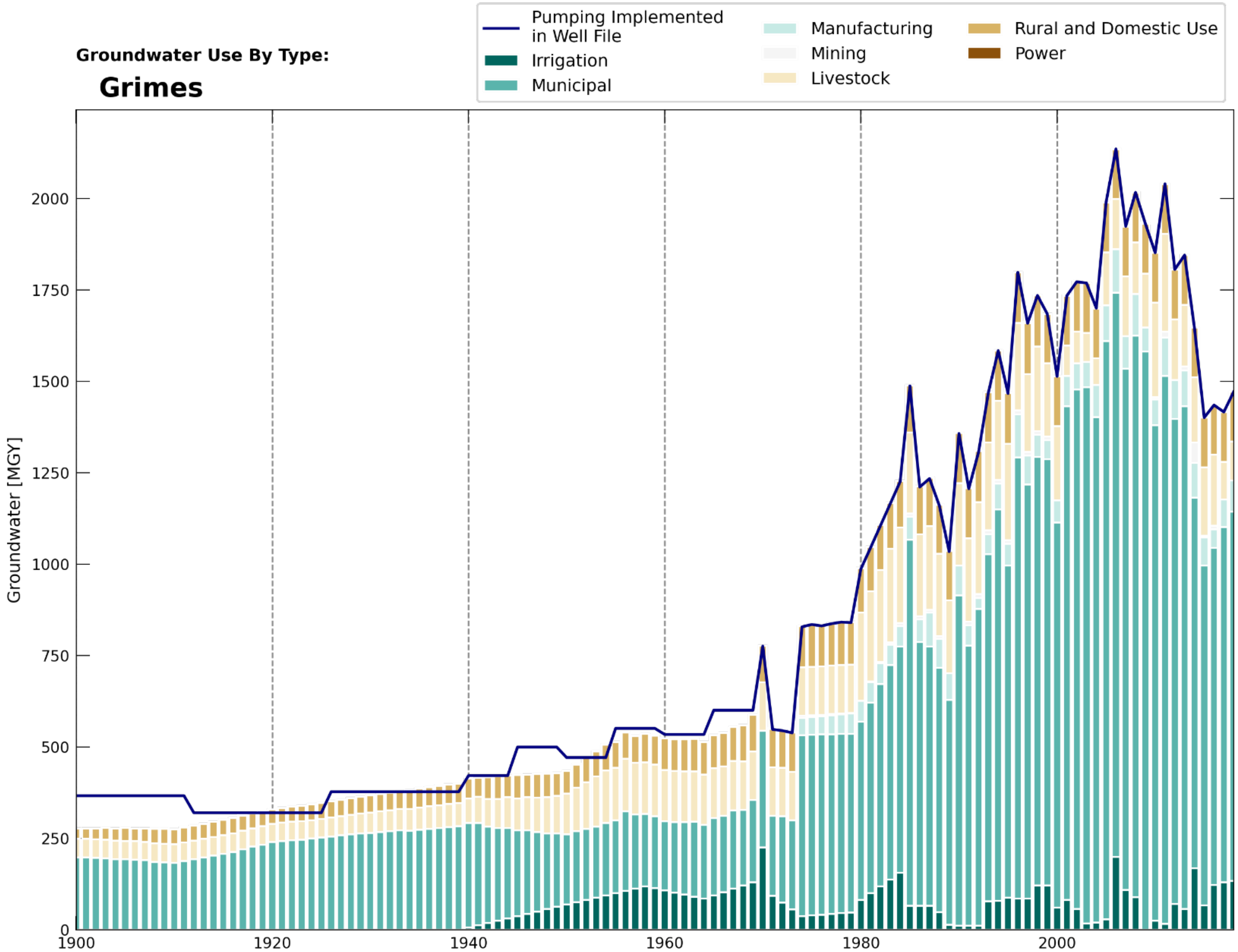

Groundwater Use By Type:
Fayette
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
0
500
1000
1500
2000
1900
1920
1940
1960
1980
2000



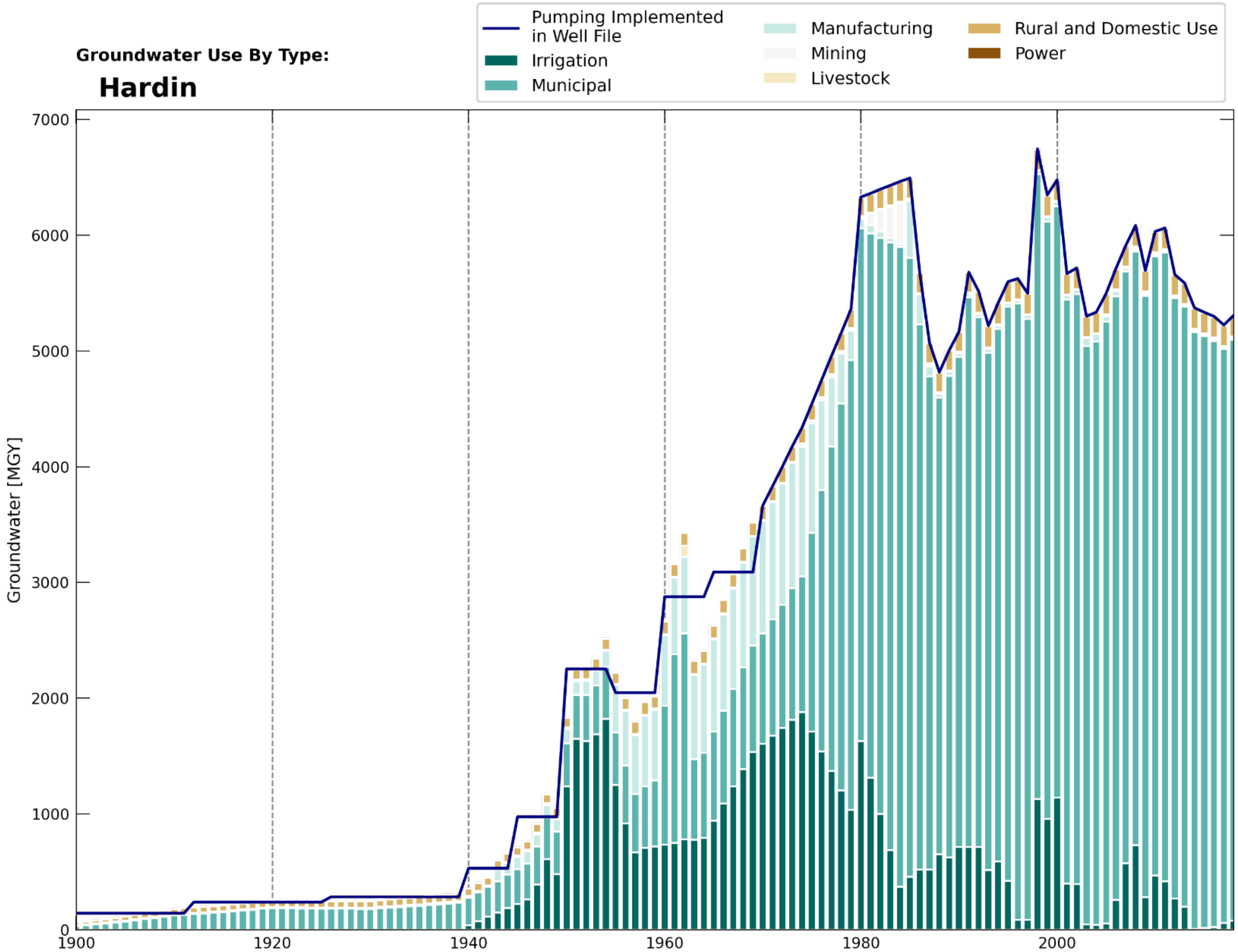
INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS



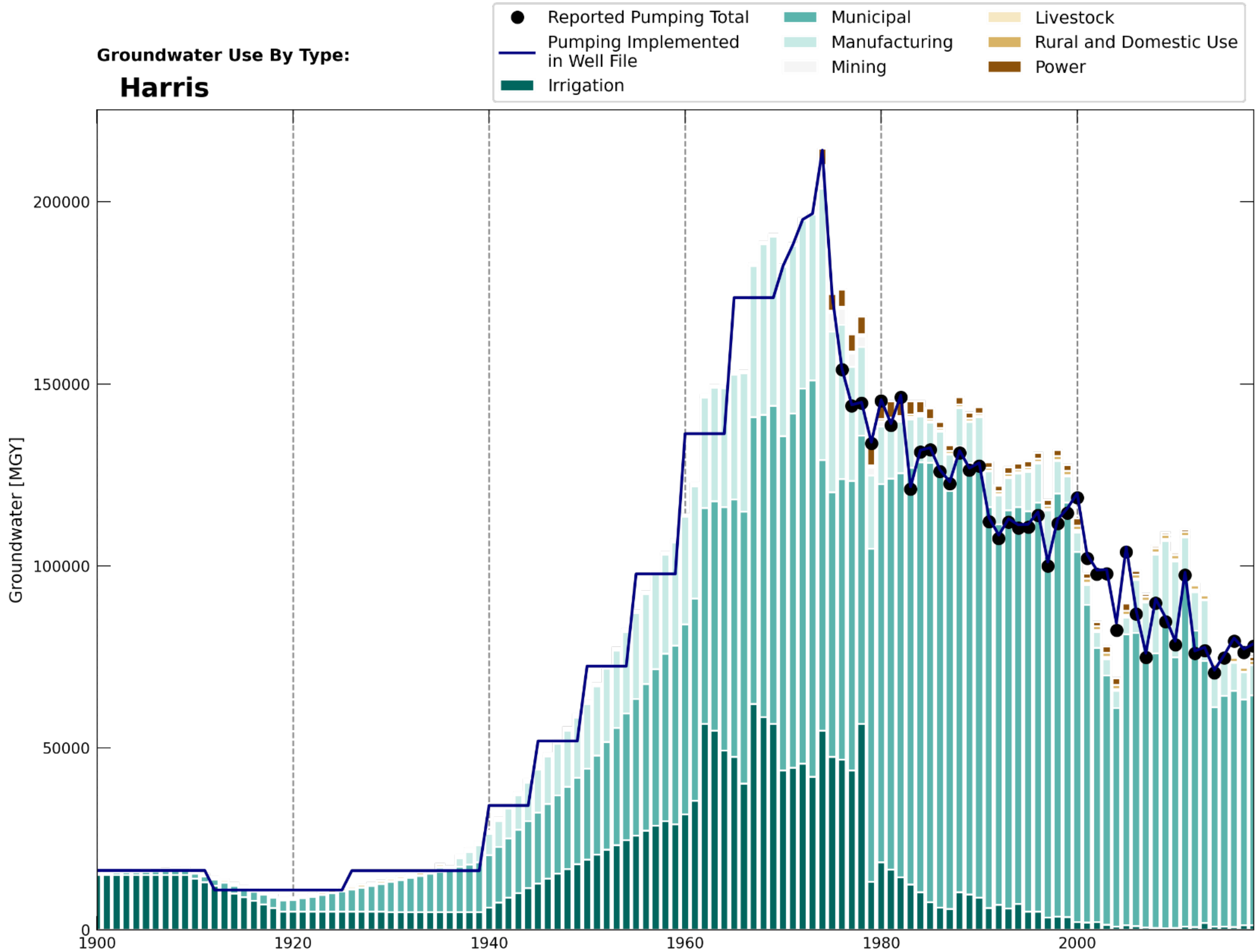
INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS



INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS



INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS



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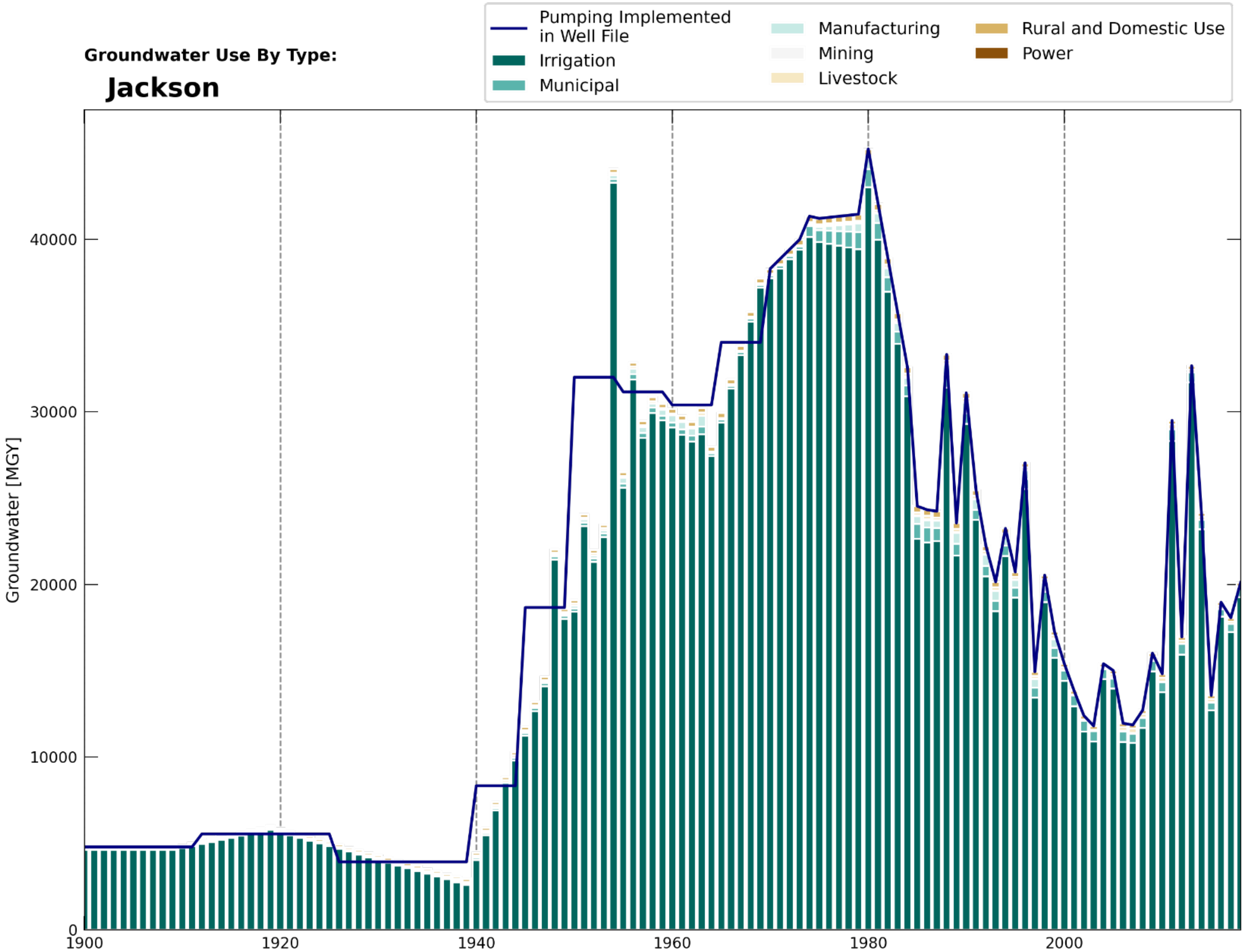

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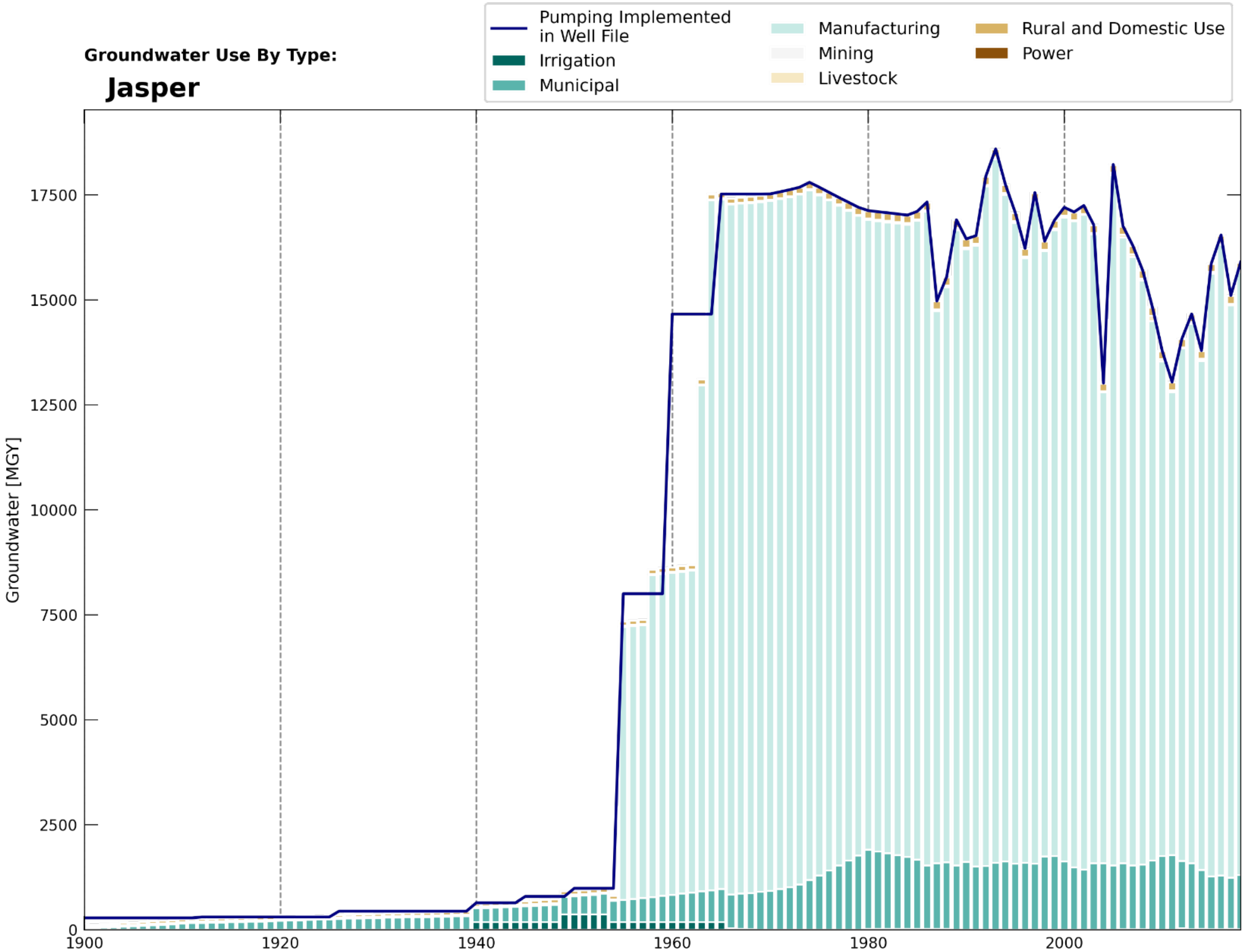

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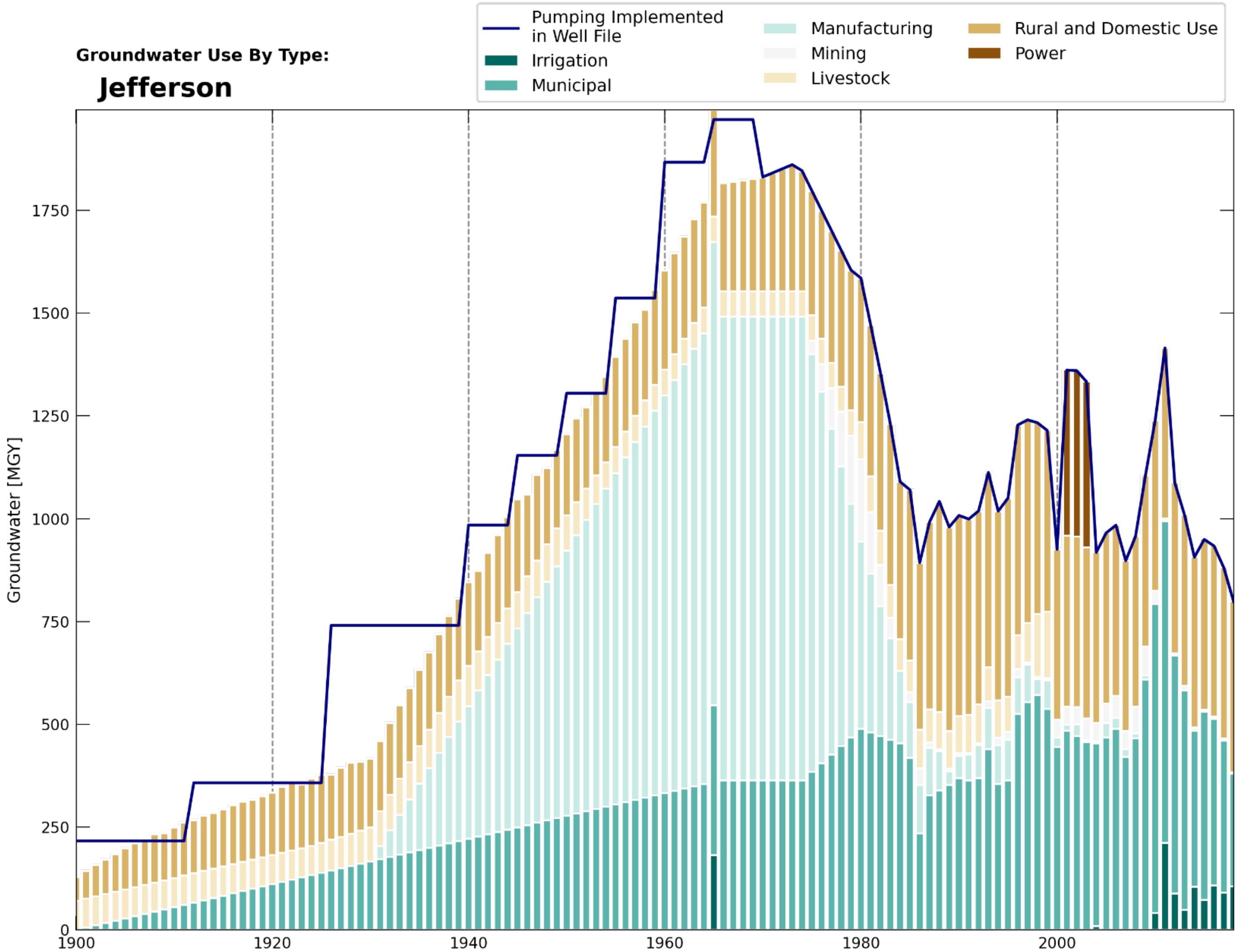

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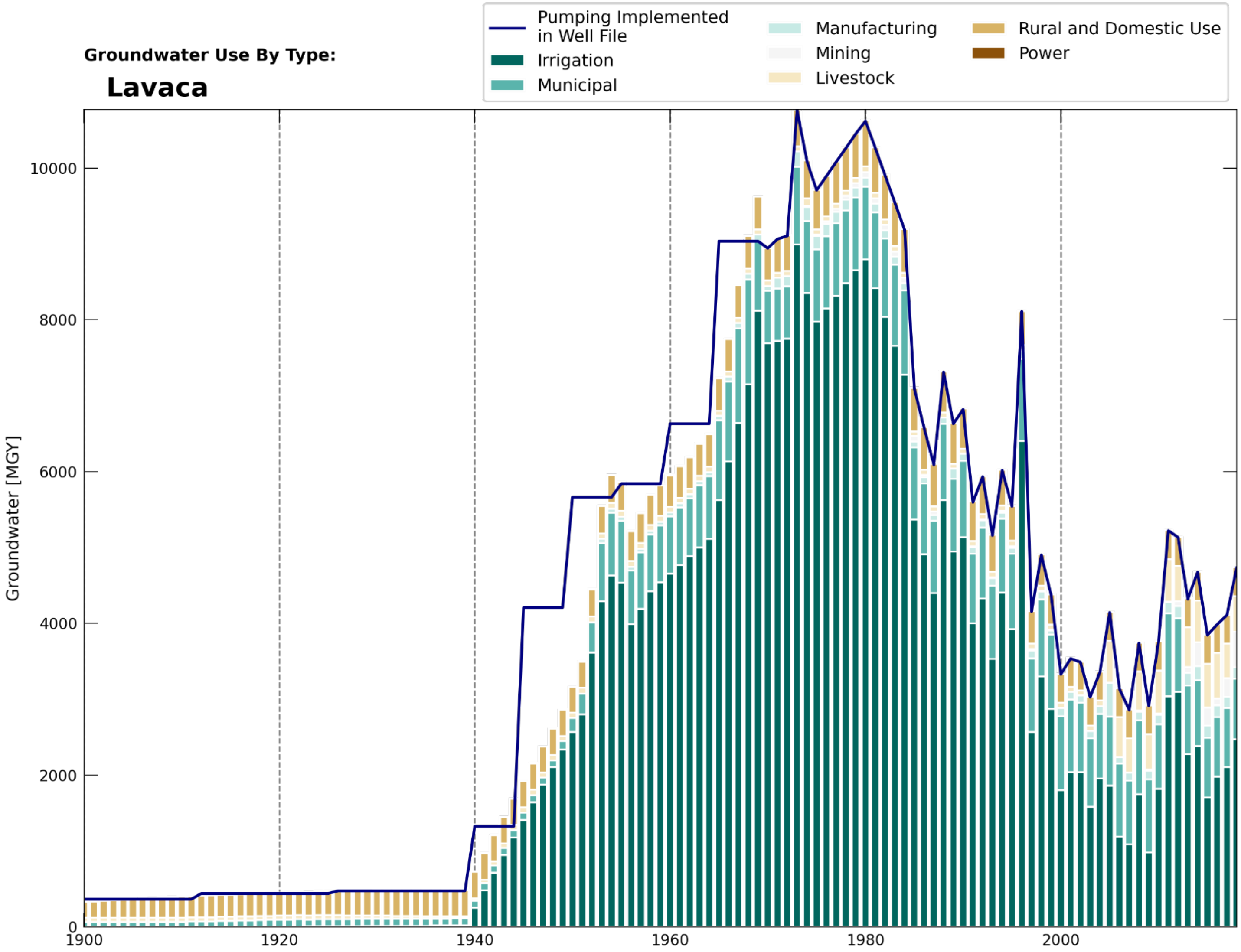

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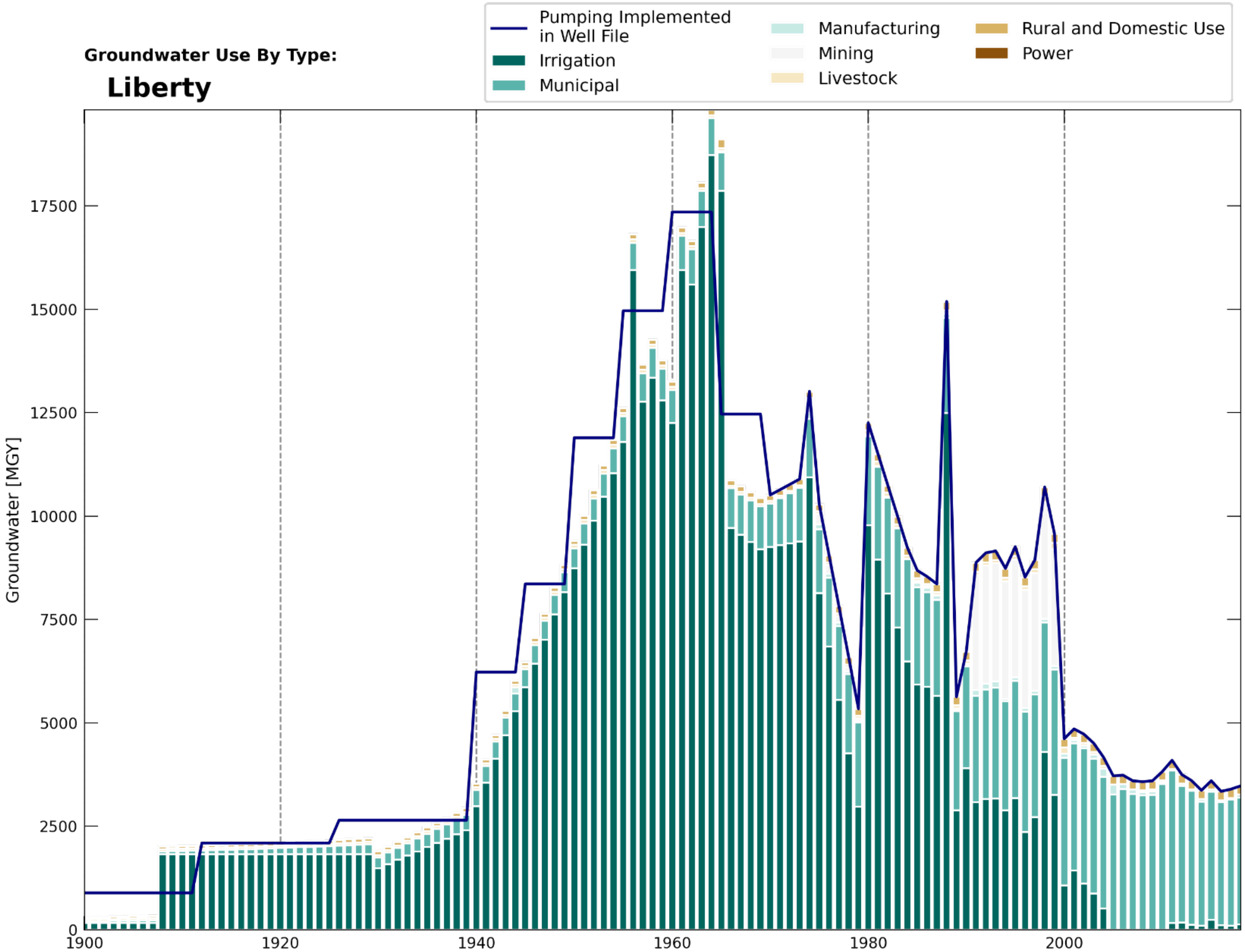

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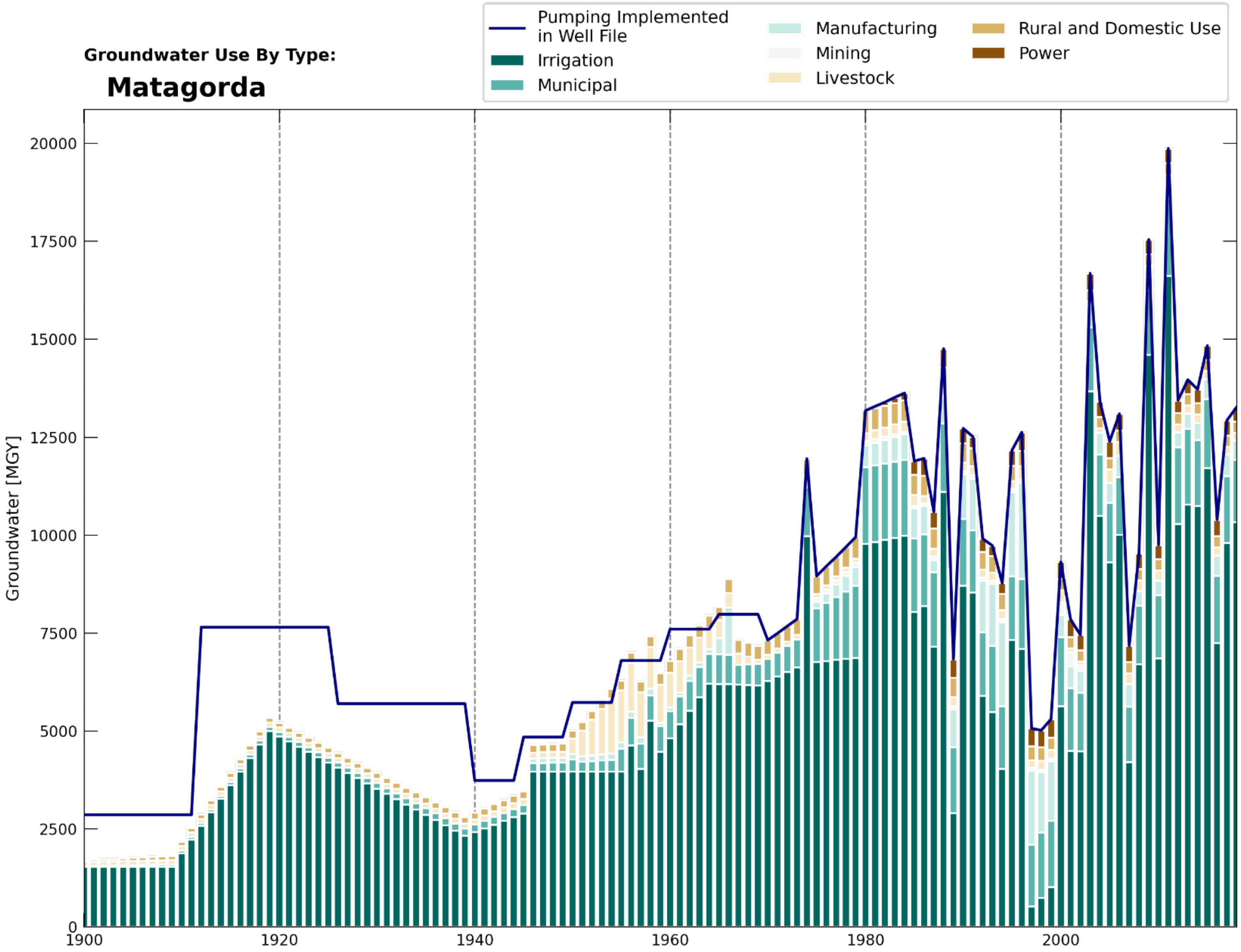
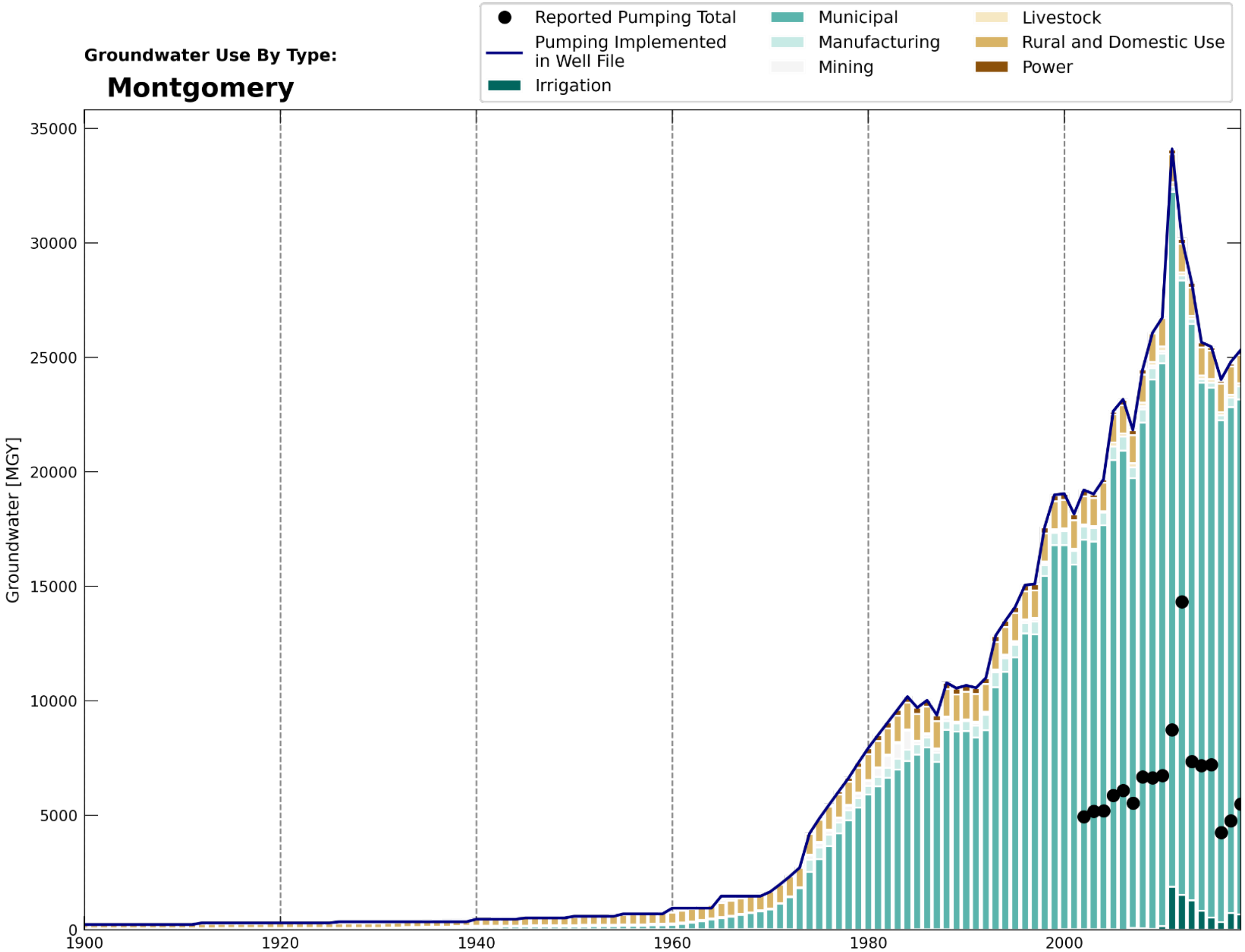
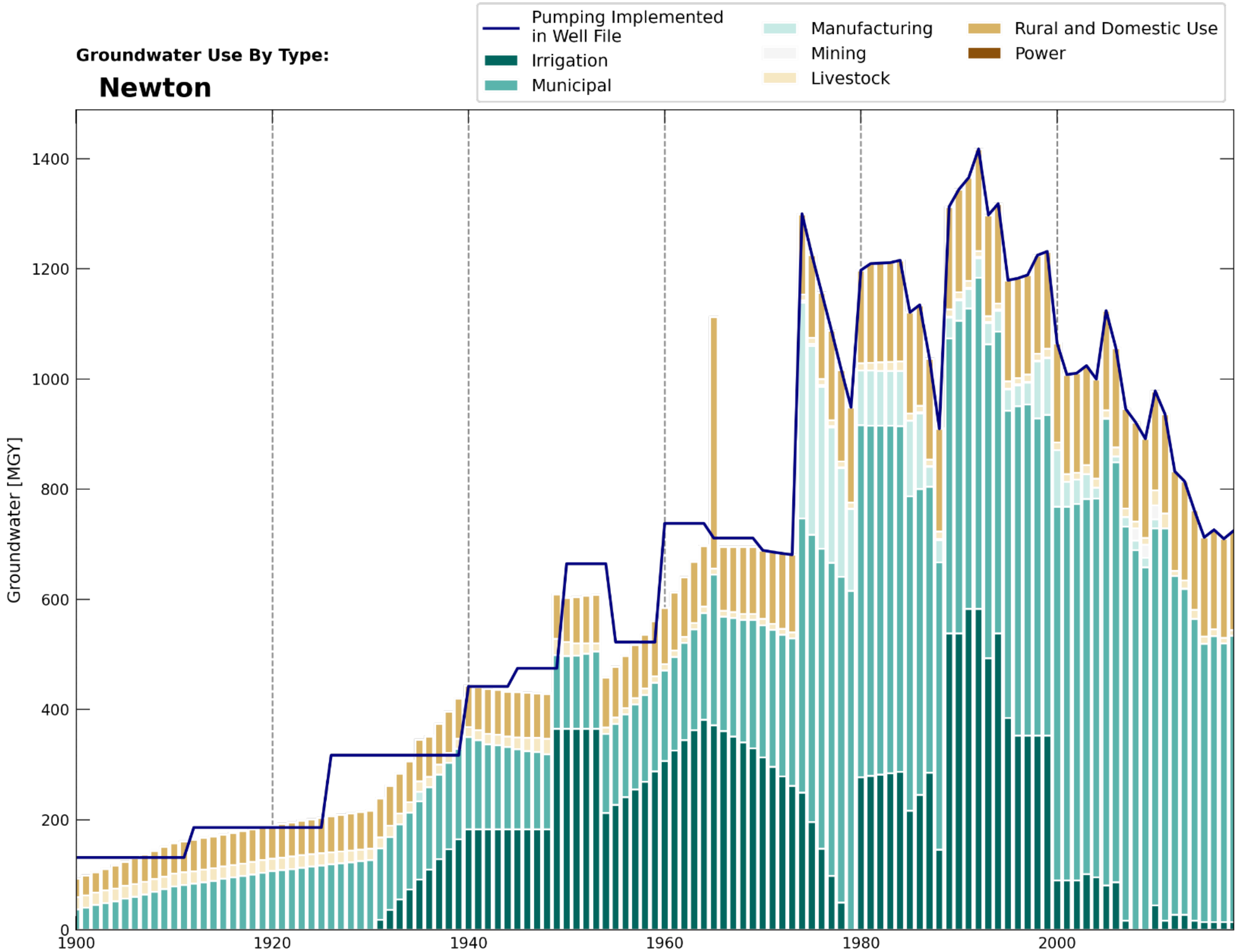


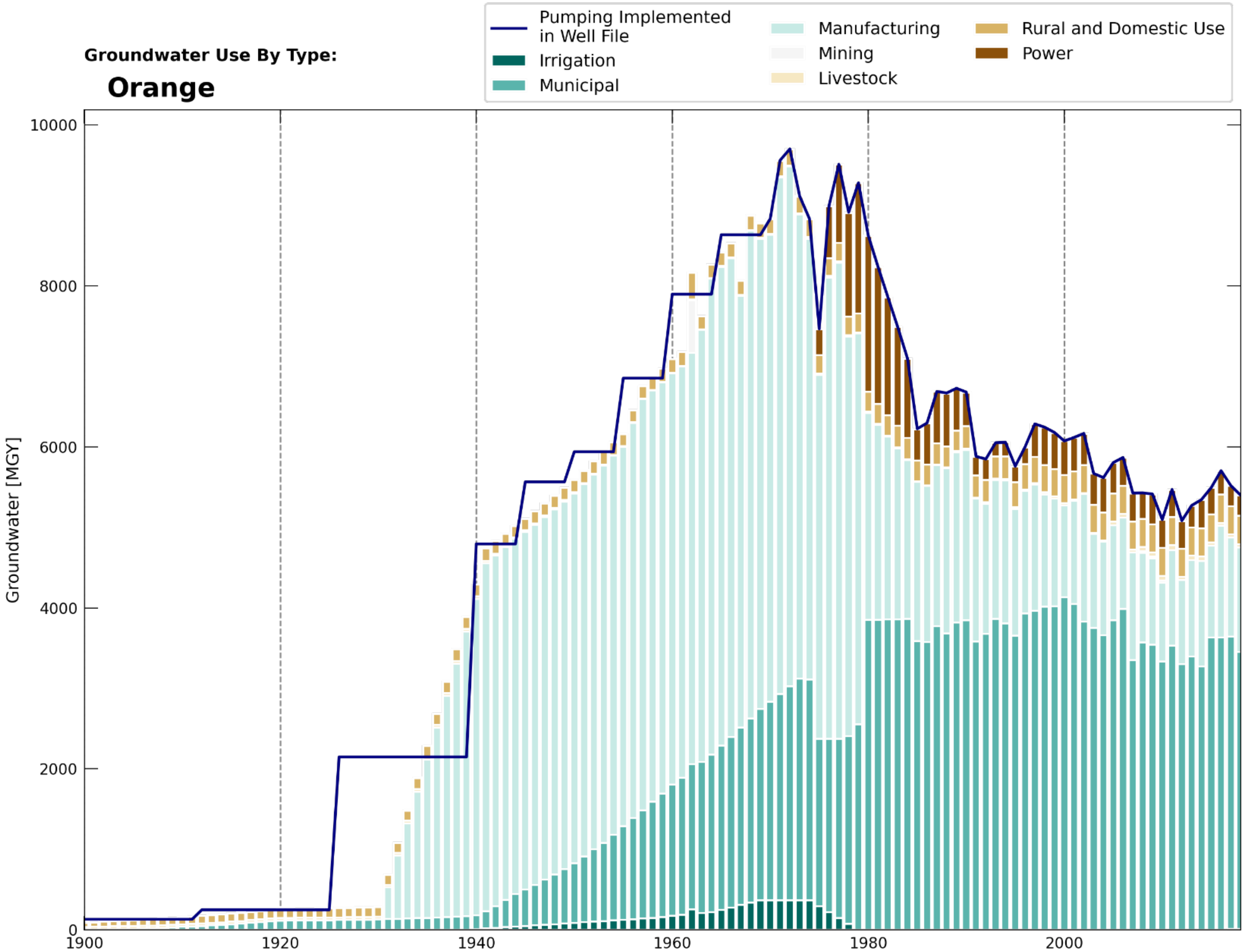
Groundwater Use By Type:
Matagorda
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
0
2500
5000
7500
10000
12500
15000
17500
20000
1900
1920
1940
1960
1980
2000



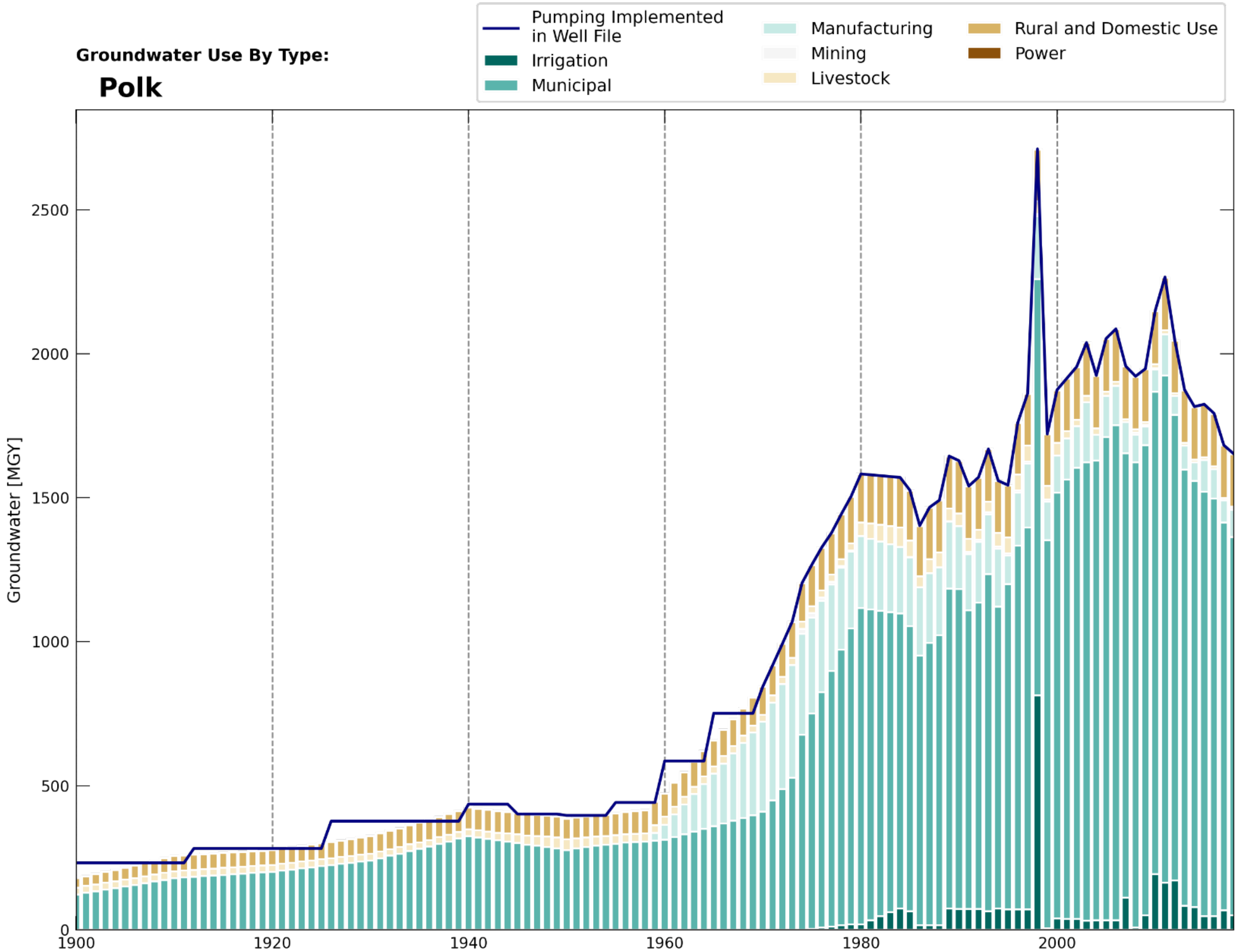
Groundwater Use By Type:
Montgomery
Reported Pumping Total
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
0
5000
10000
15000
20000
25000
30000
35000
1900
1920
1940
1960
1980
2000

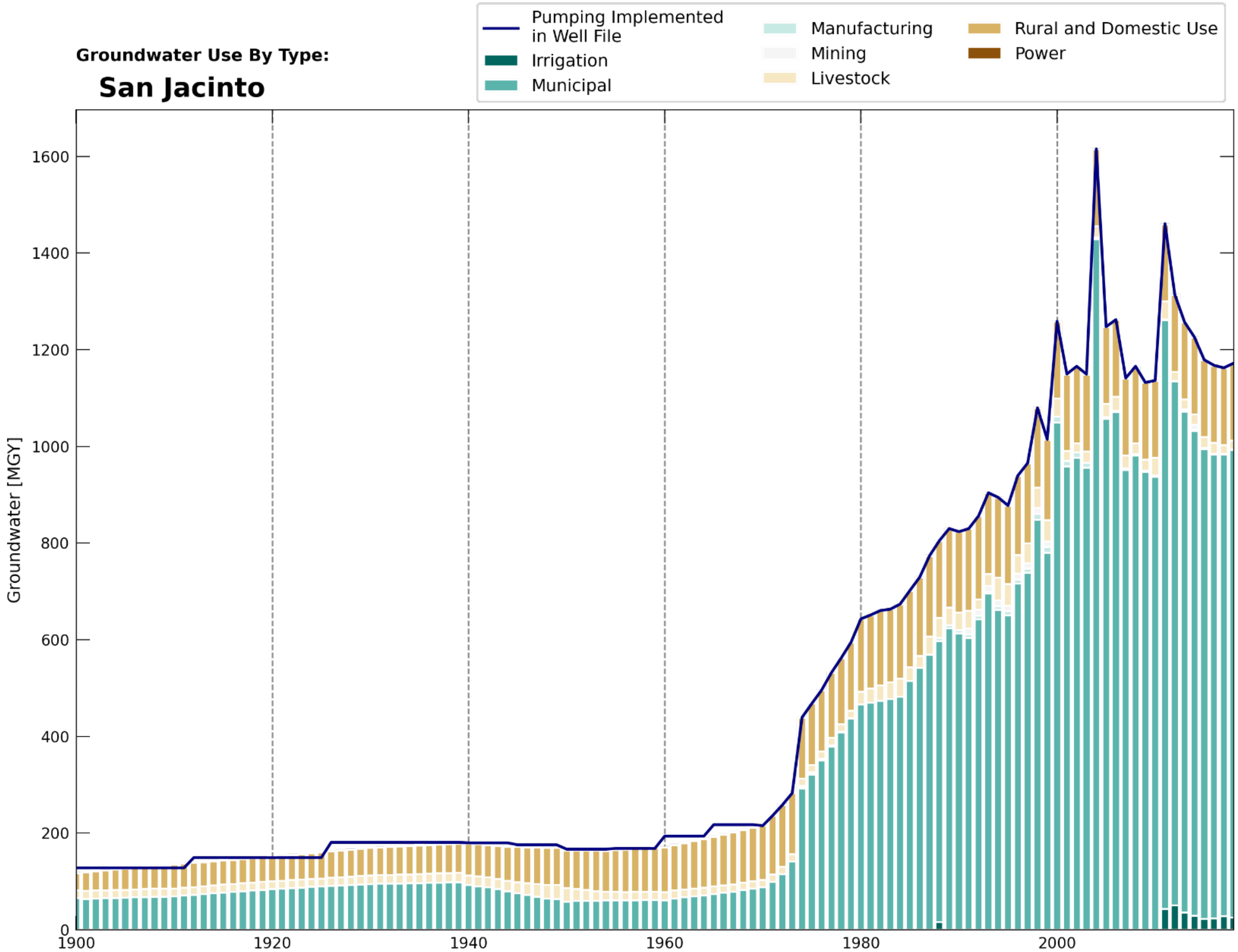


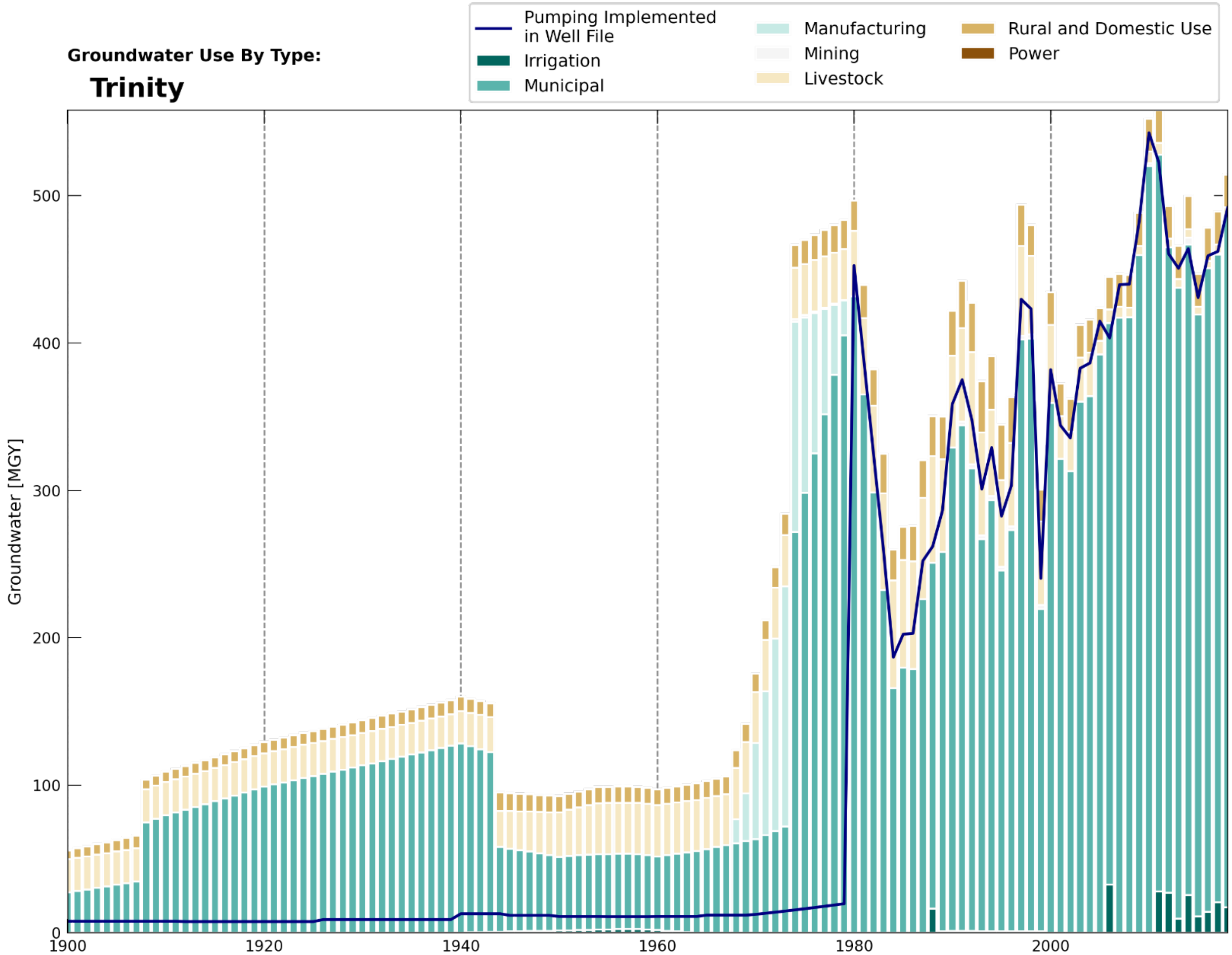
Groundwater Use By Type:
Newton
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
0
200
400
600
800
1000
1200
1400
1900
1920
1940
1960
1980
2000



Groundwater Use By Type:
Orange
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
10000
8000
6000
4000
2000
0
1900
1920
1940
1960
1980
2000


Groundwater Use By Type:
Polk
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
0
500
1000
1500
2000
2500
1900
1920
1940
1960
1980
2000


Groundwater Use By Type:
San Jacinto
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
0
200
400
600
800
1000
1200
1400
1600
1900
1920
1940
1960
1980
2000



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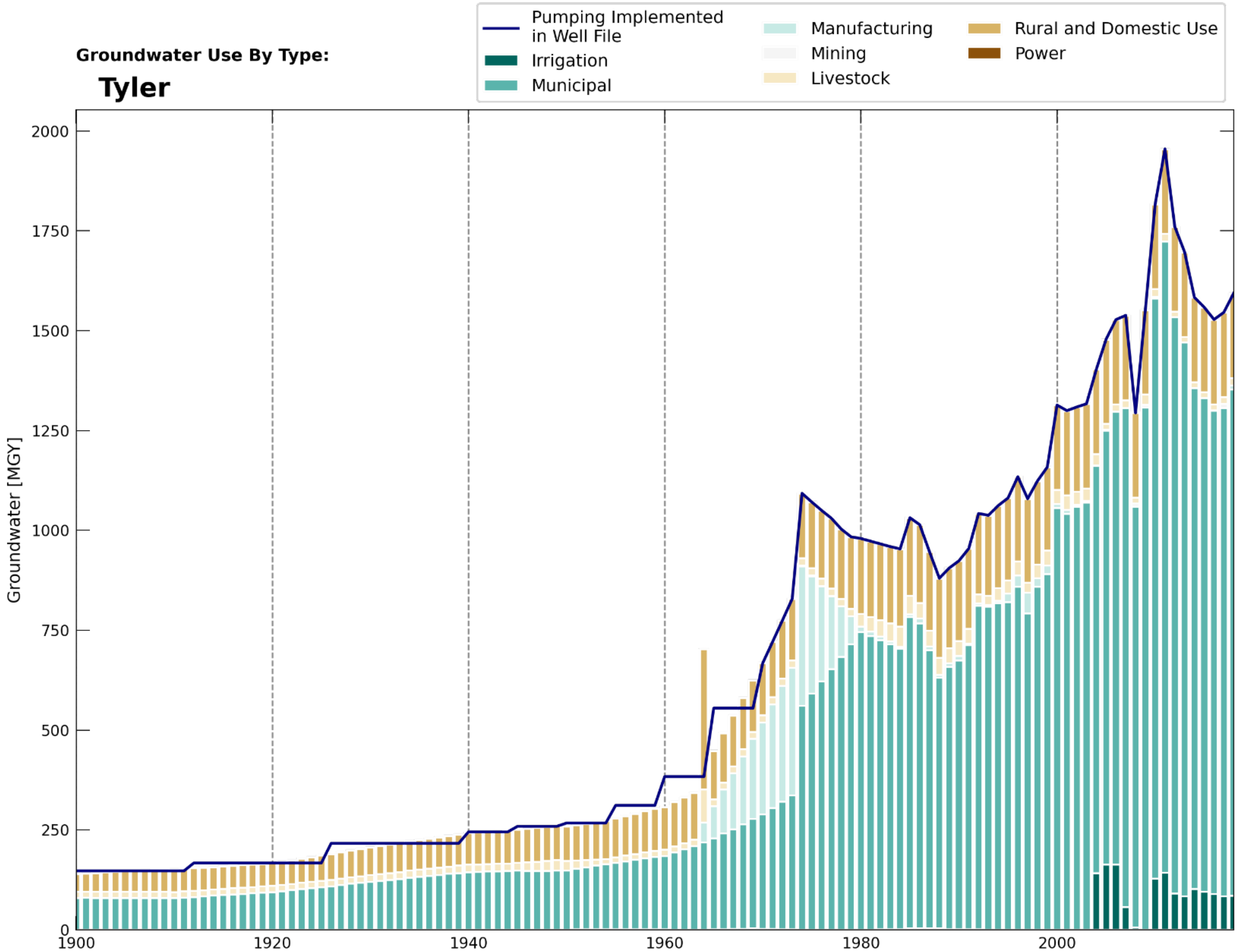
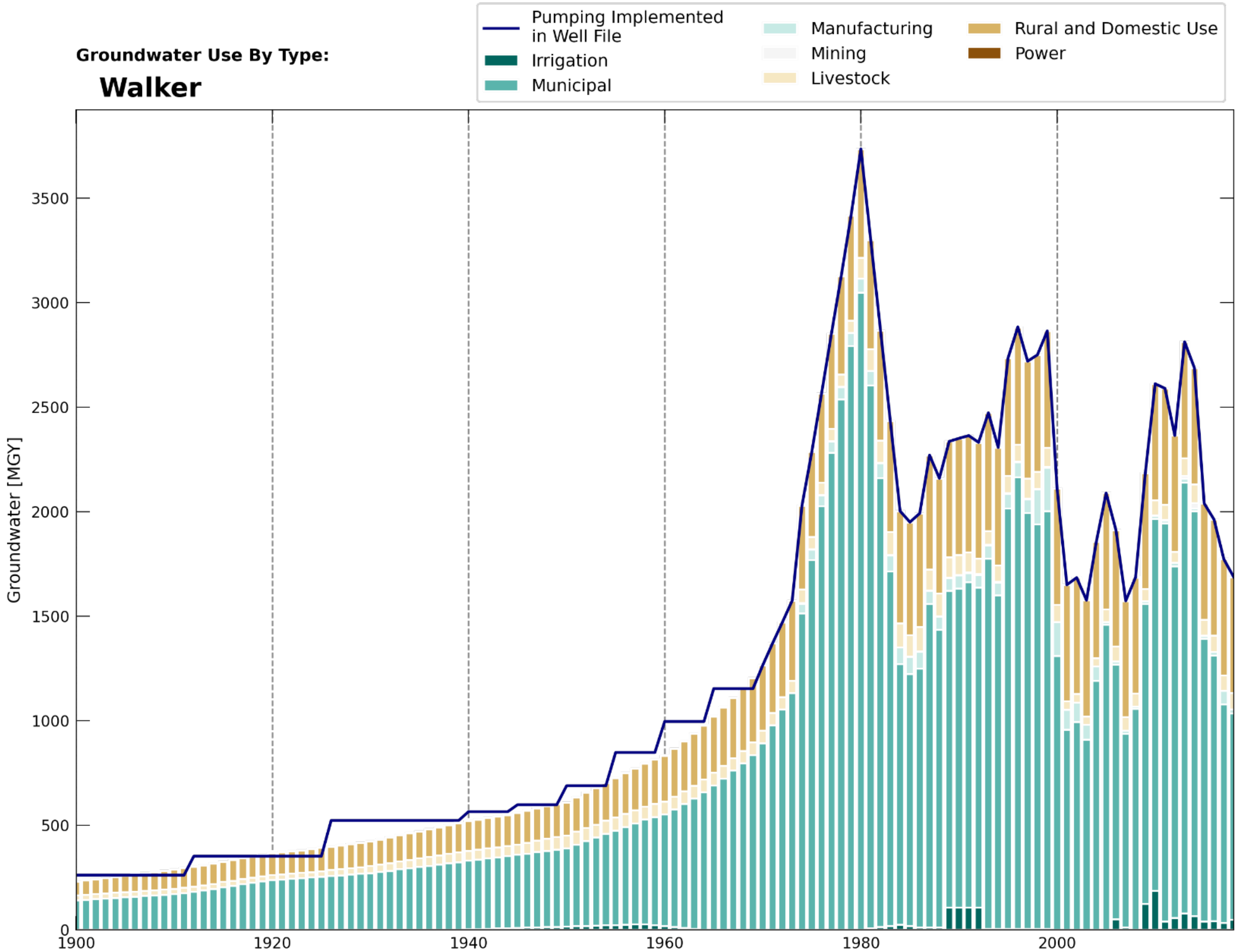

Groundwater Use By Type:
Tyler
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
0
250
500
750
1000
1250
1500
1750
2000
1900
1920
1940
1960
1980
2000



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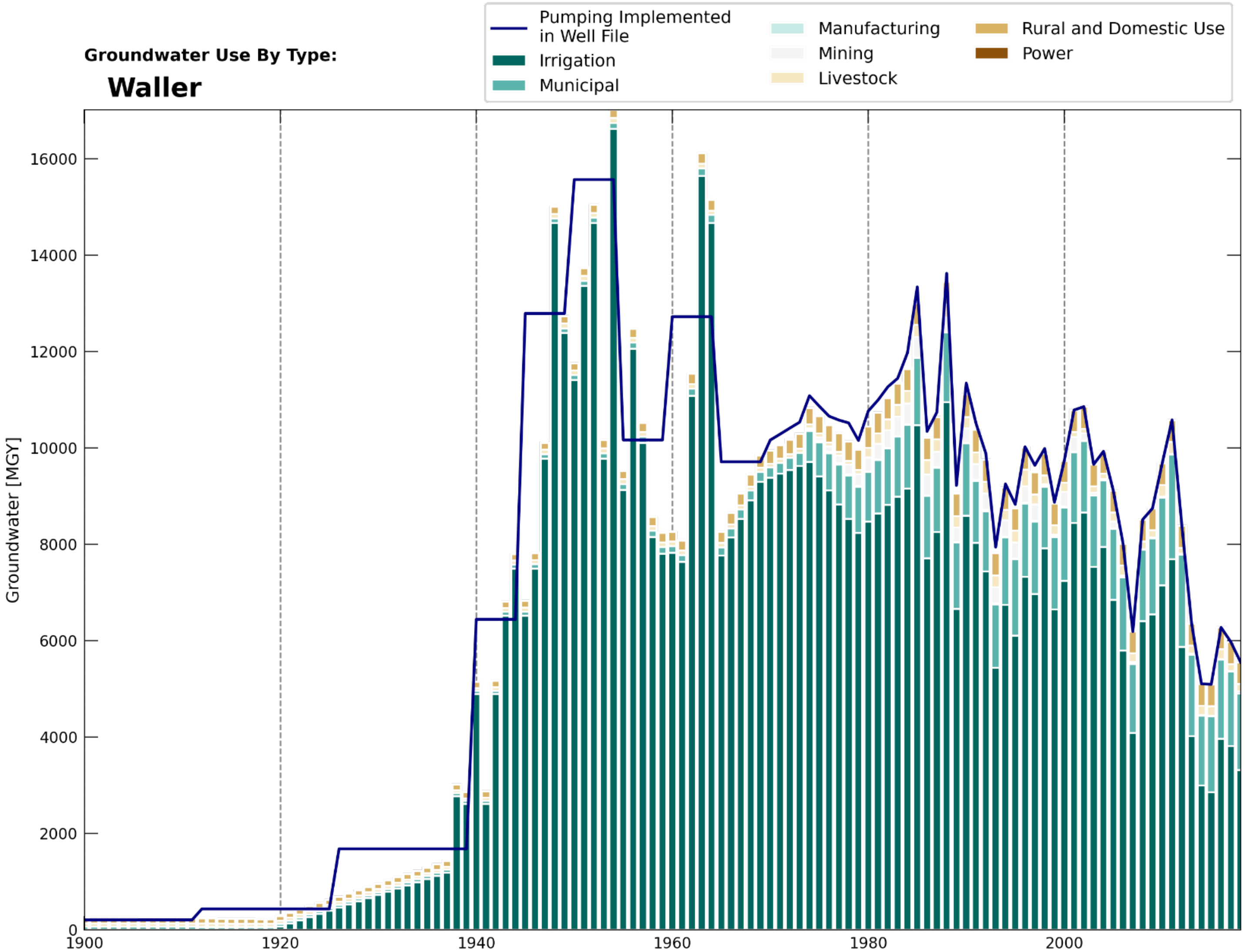

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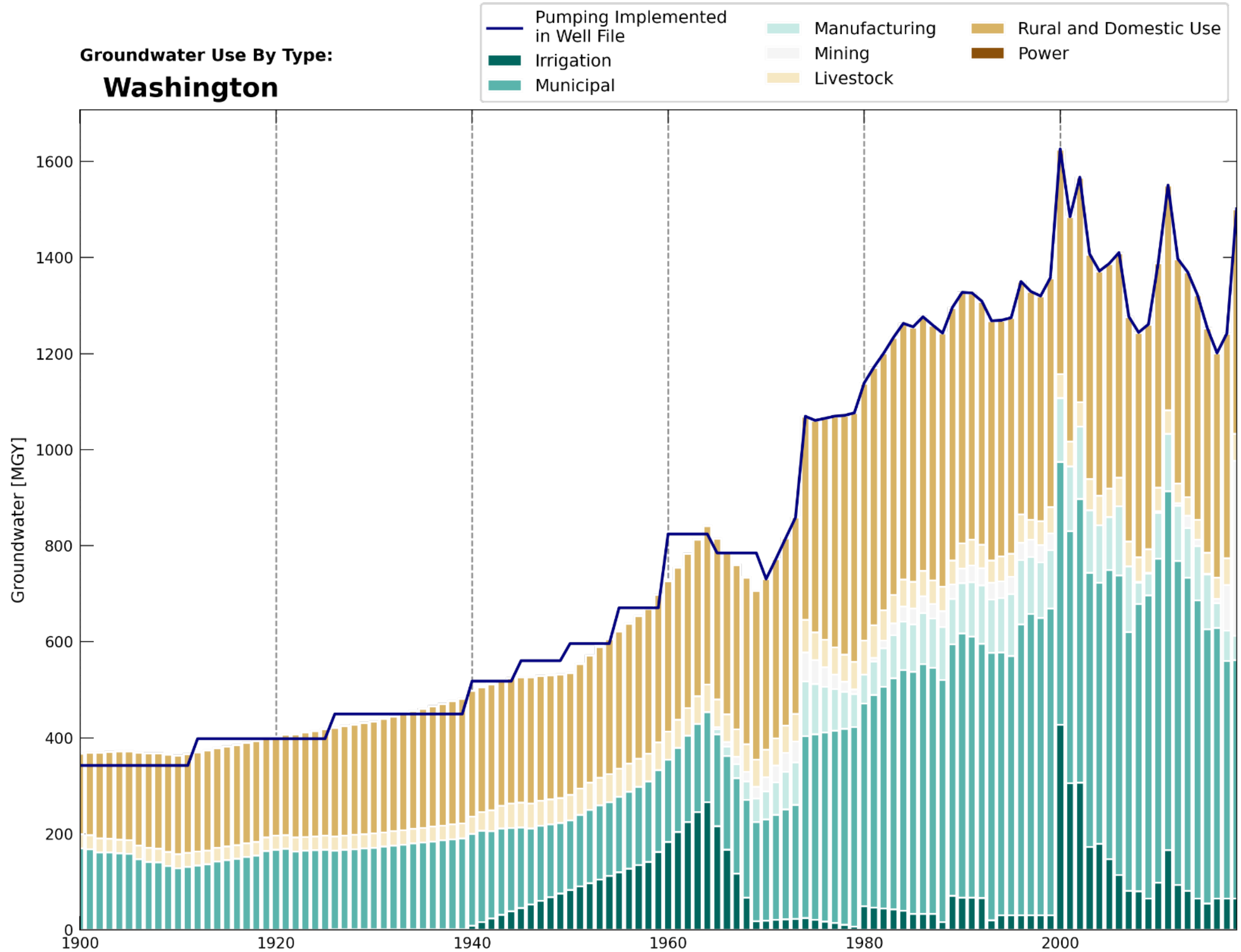
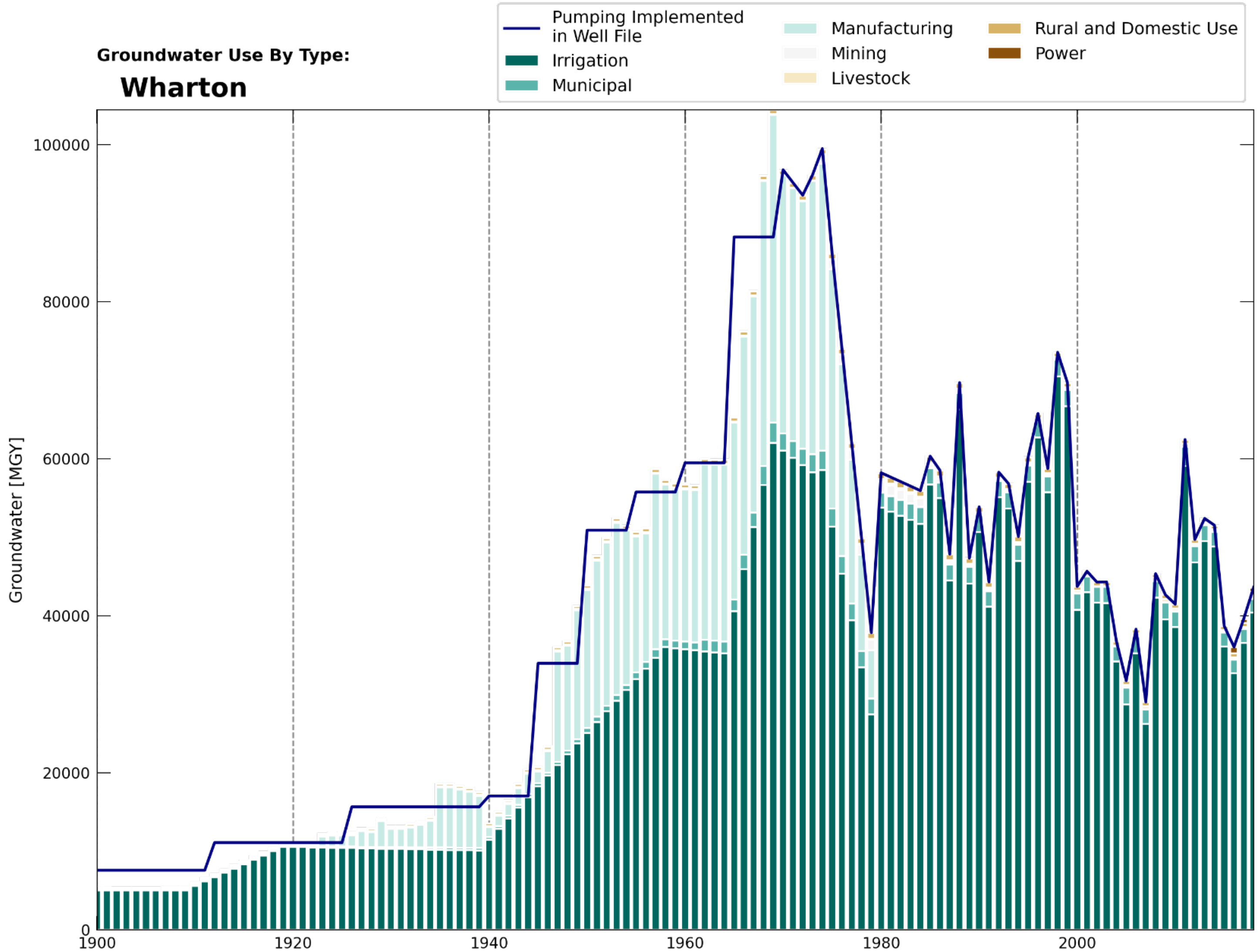


Groundwater Use By Type:
Washington
Pumping Implemented in Well File
Irrigation
Municipal
Manufacturing
Mining
Livestock
Rural and Domestic Use
Power
Groundwater [MGY]
0
200
400
600
800
1000
1200
1400
1600
1900
1920
1940
1960
1980
2000



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