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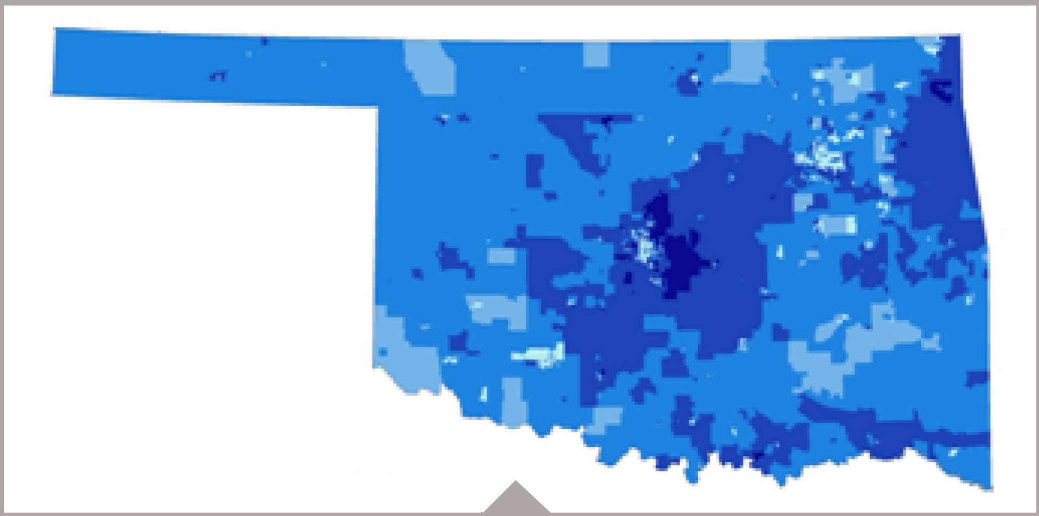
Proximity of Private Domestic Wells to Underground Storage Tanks: Oklahoma Pilot Study



Office of Research and Development
National Risk Management Research Laboratory | Groundwater, Watershed, and Ecosystem Restoration Division

Proximity of Private Domestic Wells to Underground Storage Tanks: Oklahoma Pilot Study

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Abstract

For protecting drinking water supplies, the locations of areas with reliance on private domestic wells (hereafter referred to as “wells”) and their relationship to contaminant sources need to be determined. A key resource in the U.S. was the 1990 Census where the source of domestic drinking water was a survey question. Two methods are developed to update estimates of the areal density of well use using readily accessible data. The first uses well logs reported to the states and the addition of housing units reported to the Census Bureau at the county, census tract and census block group scales. The second uses housing units reported to the Census and an estimated well use fraction. To limit the scope and because of abundant data, Oklahoma was used for a pilot project. The resulting well density estimates were consistent among spatial scales, and were statistically similar. High rates of well use were identified to the north and east of Oklahoma City, primarily in expanding cities located over a productive aquifer. In contrast, low rates of well use were identified in rural areas without public water systems and Oklahoma’s second largest city, Tulsa, each attributable to lack of suitable ground water. High densities of well use may be expected in rural areas without public water systems, expanding cities and suburbs, and legacy areas of well usage. The completeness of reported well logs was tested by counts from neighborhoods with known reliance on wells which showed reporting rates of 20% to 98%. Well densities in these neighborhoods were higher than the larger-scale estimates indicating that locally high densities typically exist within analysis units. A Monte Carlo procedure was used to determine that 27% of underground storage tanks that had at least one well within a typical distance of concern of 300 m (1,000 ft).

QA Statement

This project was performed under quality assurance project plan ORD Project QA ID #G-GWERD-0019367. In the section on "Data and Methods", the methods for assessment of the quality of data are described in the "Positional Accuracy" subsection. The "Data Error and Method Evaluation" subsection presents results on well position error, public land survey system location accuracy, 1990 census sampling error, and accuracy of historical application of the net housing unit method.

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Introduction

Throughout the world, public water supplies may be limited by municipal expansion that outpaces the extension of water systems (Kjellén 2001, Lundqvist et al. 2003, Danert et al. 2014, Wescoat et al. 2007) or restricted boundaries (Aiken 1987, Johnson et al 2004, MacDonald Gibson et al 2014). Residents then meet their water needs through connection to other residences, non-piped sources, or from private domestic wells (e.g., Jepson and Brown 2014, U.S. GAO 1998). The U.S. Geologic Survey (USGS) estimated that 14% of the U.S. population and 8% of Oklahomans provided their own domestic water in 2010 (Maupin et al. 2014), primarily through the use of private domestic wells (hereafter referred to as "wells").

In the United States, the Safe Drinking Water Act (SDWA) regulates public water systems and uses source water protection, treatment, distribution integrity, and public information as barriers between contamination and safe drinking water. Routine testing of public water supplies is required for a list of natural and anthropogenic contaminants (U.S. EPA 2004). However, private wells serving less than 25 persons are not regulated by the SDWA, and routine monitoring is not required. Less frequent testing is mandated by some states, commonly at installation and property transfers (see, e.g., Atherholt et al. 2009).

Numerous examples of private domestic well contamination demonstrate the potential risks for people who drink from private wells. The contaminants include pathogens, nitrate, arsenic, fluoride, radon, chromium VI, perchlorate, uranium, and organic compounds (including pesticides, gasoline constituents, and chlorinated solvents) (e.g., Ander et al. 2016, DeSimone et al., 2009, Schaider et al. 2016, U.S. EPA 2002). Although each of the SDWA barriers to drinking water contamination noted above is potentially involved with the safety of water from wells, the lack of systematic monitoring leads to the potential for undetected exposure of a large number of people (Levin et al. 2002), and demographic data on well users are currently limited (Vanderslice 2011). A recent workshop on private wells recommended, among other things, establishment of a standardized database of private well use, strategically incorporating existing information (Fox et al. 2016), as there are no national data on the numbers and locations of wells (Ridpath et al. 2016).

In addition, identification of users of private domestic wells is potentially useful for identifying factors influencing cancer associations in epidemiologic studies (Patel et al., 2017), pediatric disease diagnosis (CEHCID 2009), water treatment needs, strategies for protecting vulnerable populations (Zheng and Ayotte 2015), and other public health concerns (U.S. DOC 1990a). Identifying users of wells could improve emergency response to spills (MDCH 2013; NMED and U.S. EPA 2015) and improve the evaluation of risk pathways for groundwater contaminant remediation (ASTM 2015).

In the U.S., a common ground water contaminant source that potentially threatens well users is underground storage tanks (USTs). Petroleum product releases have been reported from over 530,000 underground storage tanks, with almost 71,000 cleanups remaining to be completed (US EPA 2016). One of the main potential pathways for exposure to petroleum hydrocarbons is the consumption of water from private domestic wells. Studies of the length of contaminant plumes indicate the expected extent of contamination from leaking underground storage tank sites (API, 1998, Connor et al., 2015). Although based on limited data, these studies indicate that the maximum observed extent of contaminant plumes is on the order of 500 m.

Well logs reported to the states provide a source of information for developing a nationwide estimate of well usage, but the availability of these data varies by state. Data may be incomplete for various reasons including: reporting requirements being imposed relatively recently (MDEQ 2015; OACR 2015); variable compliance with reporting requirements (OWRB 2014); lack of physical location data (MEEA 2015); exclusion of "grandfathered" wells (NDER 2015); limited ability of state agencies to compile data (PGS 2015); or legal restrictions (CDWR 2015).

Indirect data on well use were developed from areas without public water by negative inference from a state-wide dataset on water supply pipelines in New Hampshire (Hayes and Horn, 2009). Indirect national data on well use were also developed after the U.S. Congress authorized a housing survey in 1939. Beginning in 1960 and continuing through 1990, a question on the source of water supply was added to the long form census asking if water was obtained from a public water supply, individual well or other source (U.S. DOC 2009). Respondents were instructed to indicate an individual well if it supplied four or fewer residences (U.S. DOC 1993).

The source of water continued as a question on the American Community Survey, and was subsequently transferred to the American Housing Survey. The current sample size of 55,000 in rural areas and more than 5,000 in 21 selected metropolitan areas is not adequate to present results on a county or smaller spatial basis after 1990 (Eggers 2009). Thus, Earle et al. (2011)

inferred well usage from the 1990 U.S. census and developed a relationship to gas station location data for estimating the potential for contamination of wells by leaking underground storage tanks. Mashburn et al. (2013) based domestic groundwater use estimates on 1990 census data and the estimated population living outside the areas of public water supply. Because these studies relied on the 1990 census data, a time and potentially spatial-resolution gap exists in high-resolution estimates of well usage.

The purpose of this work was to develop a method to update 1990 estimates of well usage from publically-available data and to determine the relationship between underground storage tanks (USTs) and wells in a pilot study. The study was designed so the method would be extensible to the entire U.S.

Data and Methods

Study Area

Because the state of Oklahoma freely distributes reported-well data and underground storage tank data, Oklahoma was selected for the pilot study (Figure 1). Water resources in Oklahoma include two major river systems (the Red and the Arkansas Rivers), ten major bedrock and eleven major alluvial aquifers (OWRB 2012). Of interest to this study are major aquifers, including the formations of the Hennessey Group, the Garber Sandstone and the Welling formation, which yield small to moderate amounts of fair quality water (Bingham and Moore 2004) and are considered major aquifers (Figure 2). Cities adjoining Oklahoma City to the east use public wells to tap the Garber-Wellington Aquifer (Figure 2 and Figure 3), as well as using surface water supplies from reservoirs (Edmond 2009). In contrast, Tulsa is situated over shale, sandstone, and thin coal beds of the Seminole formation, which yield small amounts of poor quality water that are insufficient for public supplies (Engineering and News Record 1924; Clinton 1945). For the most part, public supplies dominate in the areas around Tulsa, with the exception of an area in Sand Springs, Oklahoma, which has no public supplies (OWRB 2017) and is situated along the Arkansas River where terrace deposits supply good quality water (Marcher and Bingham 1989, Figure 2). Similarly, Enid, Oklahoma is situated over the Enid Isolated Terrace Deposit which supplies moderate amounts of fair to good quality water (Bingham and Bergman 1980) and forms the supply for the city water system.

Figure 1. Map of the United States showing the location of Oklahoma.

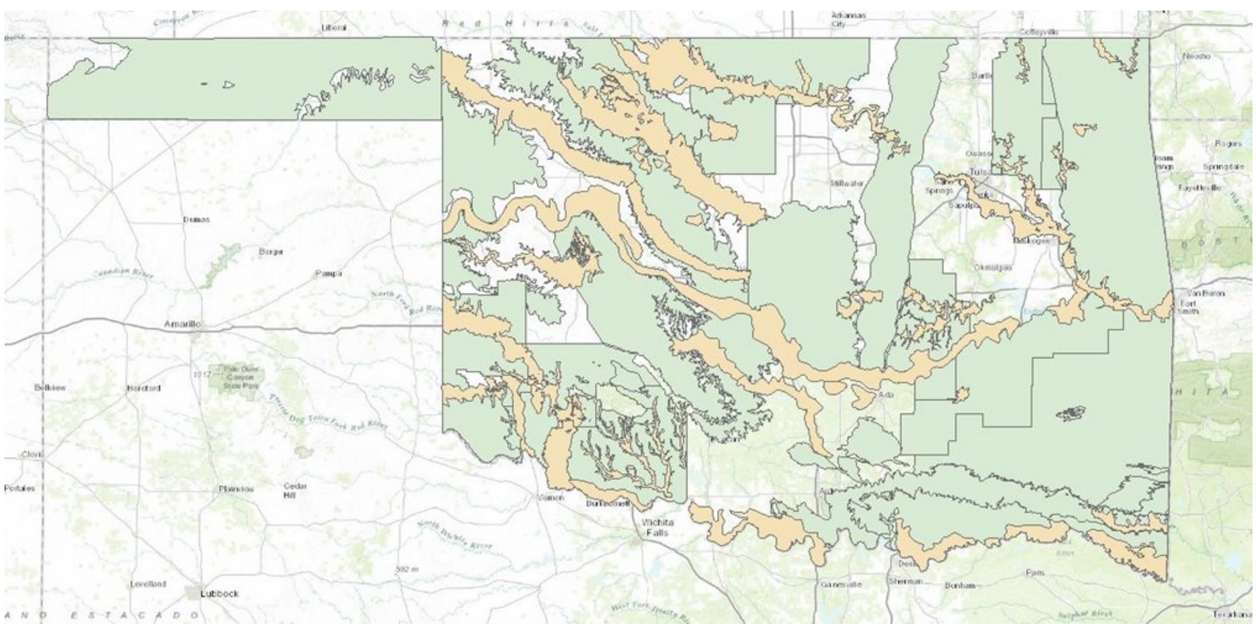


Figure 2. Major (green) and alluvial (brown) aquifers of Oklahoma (Oklahoma Water Resources Board, 1998).

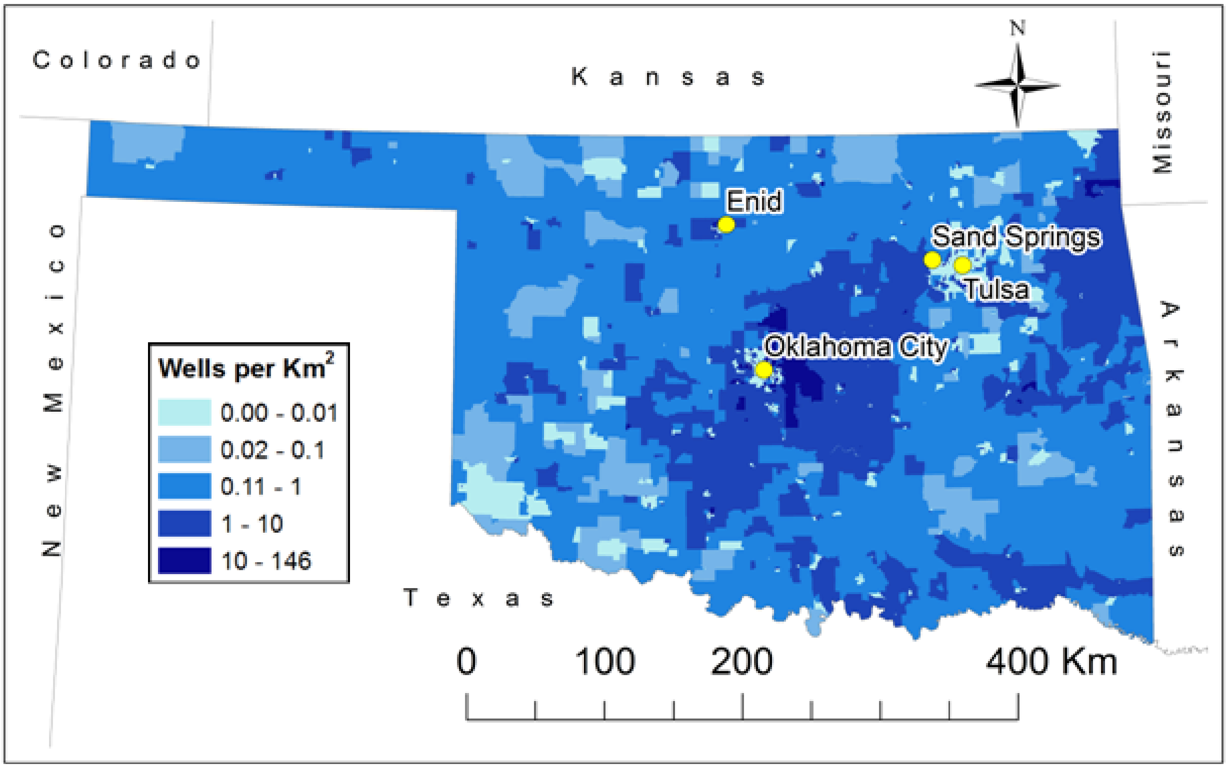


Figure 3. Density of housing units using private domestic well use inferred from 1990 Census on a census block group spatial basis, with locations of cities discussed in the text.

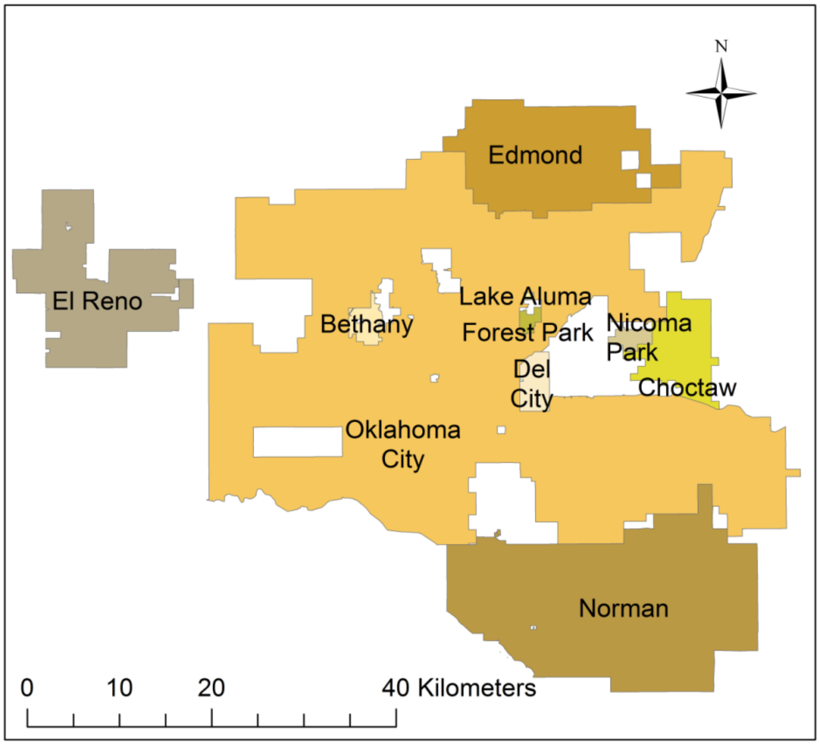


Figure 4. Locations of Oklahoma cities discussed as examples in the results section.

Well Log Data

The Oklahoma Water Resources Board (OWRB) distributes compiled data from well logs reported under the state's well driller registration requirements (OACR 2015, OWRB 2015a). Well locations are either estimated by location within the U.S. public land survey system (PLSS) township-section system or reported as latitude-longitude, which became a requirement after 2009.

Water supplies in Oklahoma

Many independent cities and unincorporated areas either border Oklahoma City or are contained within the same county (Figure *4*). These include communities with no water systems (Forest Park, Nicoma Park, and Lake Aluma), areas of historical private domestic well usage (Bethany, Oklahoma, see Jacobsen and Reed, 1949), and cities with water systems which do not serve their entire populations (i.e., Choctaw, Del City, El Reno, Edmond, and Oklahoma City (Edmond 2009, Layden 2013, OWRB 2017)), and allow use of private wells, although sometimes limited to lots of a certain size or larger (e.g., Edmond, 2017).

Estimation Methods for Counties, Census Tracts and Census Block Groups

From U.S. Census, USGS, and Oklahoma Water Resources Board (OWRB) data, two approaches were developed for estimating the density of private wells. To address scale and zoning issues, associated with administrative units (Salmivaara et al. 2015), the results are compared at the county, census tract, and census block group administrative levels. The first method is based on the number of reported wells (RW) and housing units lost during a specified time period:

(1) $$\rho_{pdw-est} = \rho_{pdw-init}\left(\frac{A_{init}}{A_{new}}\right) + \Delta\frac{N_w}{A_{new}} - f_{pdw}\frac{N_{HU-lost}}{A_{new}}$$

where $\rho_{pwd-est}$ is the well density estimate over an area of A_{new}, $\rho_{pwd-init}$ is the initial well density over the area A_{init}, N_w is the number of wells, f_{pdw} is the fraction of well use to total water supply, and $\frac{N_{HU-lost}}{A_{new}}$ is the number of housing units lost per unit area. The initial well density and f_{pdw} are inferred from the 1990 census results. The method is applied in two increments corresponding to census years: 1990 to 2000, and 2000 to 2010. The quantity f_{pdw} is updated after each incremental calculation is made, allowing for changing spatial patterns of well use. Including the loss of housing units accounts in part for the loss of wells, as the well records may only indicate wells added.

The second method is based only on the net change in housing units (NHU):

(2) $$\rho_{pdw-est} = \rho_{pdw-init}\left(\frac{A_{init}}{A_{new}}\right) + f_{pdw}\,\Delta\frac{N_{HU}}{A_{new}}$$

where $\Delta\frac{N_{HU}}{A_{new}}$ is the net change in housing units per unit area. The fraction of private well use f_{pdw} is determined from the 1990 census results. Variants on the NHU method allow for updating of f_{pdw}. First, for calculating the 2010 well density, f_{pdw} was updated from the well logs reported through 2000. Second, county-level water use data are available from USGS from

1985 to 2010, which were used to update f_{pdw} county-level estimates for 2000 and 2010 using the NHU method.

Any estimates which produced negative well density for either method were replaced with a value of zero. Tests of statistical significance were performed on results determined for each spatial basis using Minitab 14 software. The Mann-Whitney non-parametric test was used because the results were not normally distributed.

To determine the initial density of private wells ($\rho_{pdw-init}$) and fraction of private well use (f_{pdw}) 1990 census data were used. Well use data were collected from the "long form" which was distributed to a sample of approximately 17% of the U.S. Population. Respondents were asked if their water source was public, a drilled well, a dug well, or "other". As noted by Maupin et al (2014), some water in the U.S. is self-supplied from surface water or cisterns. The smallest unit used in the pilot study is the block group, because it is the smallest unit for which the census bureau could supply sampled results (i.e., the well use data). The block groups were designed to contain an optimum of 400 housing units (US. DOC, 1990b).

Census results were gathered for counties, census tracts, and census block groups from the U.S. Census Bureau and the National Historical Geographical Information System (Minnesota Population Center 2011). Shape files containing these data for Oklahoma were joined to counties, census tracts, and census block groups to generate comparisons on three spatial scales.

The number and size of census tracts and block groups ("geographies") can change from census to census according to criteria established by the census bureau (FR 2008). The well estimates for these geographies were developed by beginning with 1990 and determining the areal density for each quantity in equations 1 and 2. To provide common-sized geographies between census years, and to account for the possibility of changing numbers of geographies, the polygon to raster tool in ArcMap 10.1 was used to generate raster datasets with a cell size of 20 m. This size was smallest which allowed for practical computation, and also caused the term A_{init}/A_{new} appearing in equations 1 and 2 to equal 1, allowing for direct comparison of quantities between years. All outputs were normalized to a shapefile containing 2010 geographies, by creating a zonal statistics table for each 2010 census tract and block group, which determined the fraction of earlier geographies contained within the 2010 land division. The 1990 and 2000 data were then assigned using the weights from the zonal statistics table. OWRB data on reported wells were joined to the 2010 shapefile in two groups covering the ten-year spans between censuses. The well densities were then determined according to equations 1, 2, and their variants.

Cities and Neighborhoods

Neighborhoods and cities that rely on solely on wells were identified by OWRB maps indicating high well density. Residences were counted from Google maps available in July 2015 and the number of wells counted from the OWRB map of reported wells (OWRB 2015b).

Positional Accuracy

Land in Oklahoma, and 34 other states is divided according to the United States Public Land Survey System (PLSS), whose principle small-scale unit is the section (250 ha, 640 ac, 1 mi^2)

(Gates and Swenson, 1968). Common subdivisions are the quarter section (64.75 ha, 160 ac), quarter-quarter section (16.19 ha, 40 ac), and quarter-quarter-quarter section (4.05 ha, 10 ac). The Oklahoma well log dataset contained wells located by five methods: global positioning system (GPS) corrected (8,103 wells), GPS uncorrected (10,060 wells), interpolation from PLSS (37,065 wells), mathematical conversion program (11,201 wells), and unspecified (3,956 wells). Well positions determined from PLSS units were assigned by OWRB to the center of the unit, and thus the maximum potential location error is equal to the distance from the center of the unit to any corner. Because each well lies within a census block group, the significant comparison was to a characteristic size of the census block groups. The potential error from the estimates was assessed with a Monte Carlo procedure where a quarter-quarter-quarter PLSS unit was randomly located within a representation of a census block group, which for simplicity was taken as a square (Figure 5). The fraction of the PLSS unit that lay outside the census block group was considered as the probability of error (see Figure 5, right). The process was repeated 100,000 times for each of the 2965 census block groups and the statistics of the results were determined.

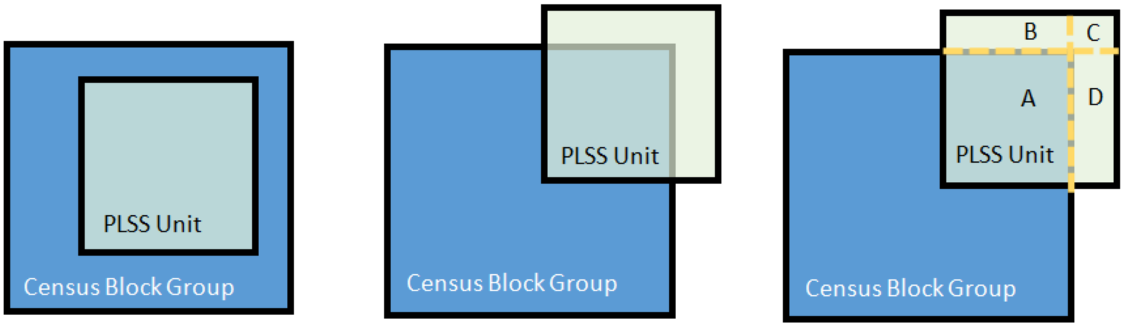


Figure 5. Spatial relationships for public land survey system (PLSS) placement in census block group error estimates. PLSS unit entirely contained within a census block group (left). PLSS unit partly outside census block group (center). Illustration of error estimate which equals (B + C + D)/(A + B + C + D) (right).

Underground Storage Tank Data

The locations of regulated underground storage tanks (USTs) were obtained from a list distributed by the Oklahoma Water Resources Board (OWRB. 2015b) and compared to reported and estimated well locations. Each of the active 3033 USTs managed by the Oklahoma Corporation Commission and the reported wells were located within a census block group. A suite of potential impact distances was chosen (15, 30, 76, 150, 230, 300 and 1,610 m), based on reported plume lengths (API, 1998, Connor et al., 2015) and knowledge of U.S. state agency programs. Next, the neighboring census block groups of each census block group were determined. The number of wells within each selected distance was determined for each UST beginning with the census block group containing the UST. Reported locations of wells were supplemented with estimated well locations in a Monte Carlo procedure. The latter were randomly selected to match the estimated RW-method well density of the census block group. The distance between the UST and each reported and estimated well was determined and the distances were binned into categories based on the chosen impact distances. The same calculations were performed on each neighboring census block group and neighbors-of-neighbors, until no more UST-to-well distances fell within the potential impact distances. Because estimated wells were included, the procedure was repeated 10,000 times, and the statistical characteristics of the binned counts of wells were determined.

Results and Discussion

Data Error and Method Evaluation

Error in reported well locations arose from three sources. First, a few wells were found to have implausible coordinates as they plotted outside the state. Second, some wells were said to occur in a county that differed from that in which they plotted. The majority of these were found to be errors in designating the county rather than error in the well position per se. This problem was particularly prevalent when the well was located near a county border, indicating that the driller may not have known the precise county boundaries. For the analysis of counties, the county designation was corrected to the county in which the well plotted. Third, some wells designated for a specified land survey system unit/subunit plotted elsewhere or were located only by reference to the PLSS unit. In total, of the 41,372 domestic wells reported between the 1990 and 2010 censuses, 2.05% (847) were omitted when a correction could not be made.

Of the wells located only by PLSS land units, the majority (99.52%) were located within a quarter-quarter-quarter section which has a maximum positional uncertainty of 140 m (center to corner). The minimum characteristic dimension of the census block groups was 236 m. Thus the positional uncertainty in these well locations is on the same order as the smallest census block group, but an order less than the median size (1,150 m), and two orders of magnitude less than the maximum-sized census block group (40,400 m). The median estimated probability of a well being placed in the wrong census block group was a maximum of 28% for the smallest census block group and dropped steadily with increased block group size. The median estimated probability is zero for all census block groups above a characteristic dimension of 474 m (area of 0.45 km^2) which accounts for 90.01% (2672) of the block groups. (Figure 6). Because the approach is to estimate the spatial density of wells within administrative units (i.e., census block group), the impact of the error in position is that the well could be assigned to an incorrect areal unit. Because this possibility exists for all adjoining administrative units, inaccurate well placement could both place wells outside a given administrative unit and, from an adjacent unit, inside an administrative unit. The result could be shifted well densities on both the maps and in calculated results, but any impacts are tempered by the positional inaccuracy being less than 140 m for 99.52% of the wells.

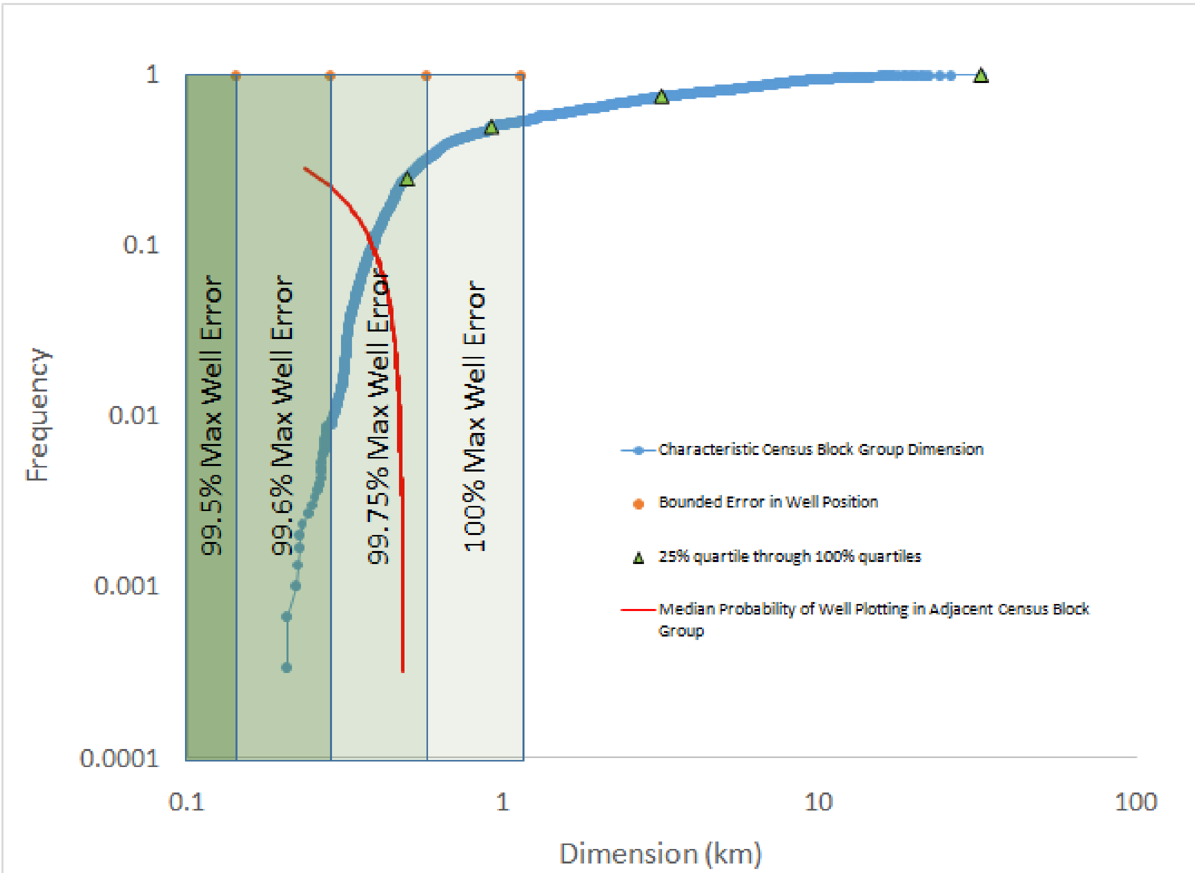


Figure 6. Frequency distribution of characteristic dimension of census block groups and relationship to public land survey system units. "Max Well Errors" follow from the size distribution of reported well locations within PLSS units of which 99.5% are smaller than the smallest characteristic dimension of the census block groups (blue line). The red line represents the median probability of a well plotting in an adjacent census block group as determined by Monte Carlo analysis.

As a check on the well use and housing unit census results for 1990, the fraction of well use was calculated by dividing the number of well users by the number of housing units and also by dividing by the sum of the four reported water uses (public, drilled well, dug well, and other). A comparison of the two calculations found that the median absolute value of the difference was 9% with a range of 0 to 199%. A second check addressed sampling error. Because they are not derived from a 100% survey, the 1990 well use results are subject to sampling errors (US DOC, 1993). For each Oklahoma county, the census bureau provided the percent of housing units sampled and a formula for calculating the sampling error (US DOC, 1993 and Table 1). Following this approach, the composited sampling error for the entire state of Oklahoma was 0.60%. For the individual counties, the sampling error ranged from 1.9% to 32%, with a median of 5.6% (Table 1). These results indicate increasing sampling error with increasing sparseness of well use, as the maximum error occurred in a county with only 68 wells (Figure *7*). The associated error is only 22 wells or 0.01% of the 1990 estimate.

Table 1. Error estimates for the 1990 census inference of private domestic well use.

County	1990 Wells	1990 Housing Units	Percent-in-Sample	Standard Error[(a)]	Percent-in-sample Design Error[(b)]	Estimated Total Sample Error	Error Fraction
Adair	3,258	7,124	24.6	94	1.2	113	0.035
Alfalfa	773	3,357	39.6	55	0.6	33	0.042
Atoka	1,274	5,110	18.5	69	1.2	83	0.065
Beaver	1,522	2,923	31.7	60	0.6	36	0.024
Beckham	1,448	9,117	17.2	78	1.2	94	0.065
Blaine	1,544	5,729	28.3	75	1.2	90	0.058
Bryan	2,958	14,875	19.8	109	1.2	131	0.044
Caddo	4,594	13,191	28.1	122	1.2	147	0.032
Canadian	3,597	28,560	14.4	125	1.3	163	0.045
Carter	2,557	19,201	16.3	105	1.2	126	0.049
Cherokee	4,182	15,935	13.5	124	1.3	161	0.039
Choctaw	2,363	6,844	18.9	88	1.2	106	0.045
Cimarron	539	1,690	36.6	43	0.6	26	0.048
Cleveland	10,928	71,038	13.9	215	1.3	280	0.026
Coal	348	2,725	31.7	39	0.6	23	0.067
Comanche	1,280	43,589	15.2	79	1.2	95	0.074
Cotton	376	3,152	24.4	41	1.2	49	0.130
Craig	582	6,041	19	51	1.2	62	0.106
Creek	4,765	25,143	18.5	139	1.2	167	0.035
Custer	1,276	11,636	18.5	75	1.2	90	0.071
Delaware	8,159	16,808	15.5	145	1.2	174	0.021
Dewey	787	2,733	40.6	53	0.6	32	0.040
Ellis	838	2,449	36.3	53	0.6	32	0.038
Garfield	2,793	26,502	16.2	112	1.2	134	0.048
Garvin	2,293	11,932	20.9	96	1.2	115	0.050
Grady	6,194	17,788	19.4	142	1.2	170	0.028
Grant	449	2,955	40.3	44	0.6	26	0.058
Greer	272	3,126	23.9	35	1.2	42	0.155
Harmon	68	1,793	17	18	1.2	22	0.319
Harper	457	2,077	41.3	42	0.6	25	0.055
Haskell	1,557	5,138	28.7	74	1.2	88	0.057
Hughes	1,234	6,021	24.1	70	1.2	84	0.068
Jackson	657	12,125	19.4	56	1.2	67	0.102
Jefferson	493	3,522	41	46	0.6	28	0.056
Johnston	1,062	4,478	21.8	64	1.2	76	0.072
Kay	1,329	22,456	22	79	1.2	95	0.071
Kingfisher	1,225	5,791	22.7	69	1.2	83	0.068
Kiowa	436	5,645	28.4	45	1.2	54	0.123
Latimer	308	4,303	15.3	38	1.2	45	0.147

County	1990 Wells	1990 Housing Units	Percent-in-Sample	Standard Error[(a)]	Percent- in-sample Design Error[(b)]	Estimated Total Sample Error	Error Fraction
Le Flore	2,185	18,029	21.7	98	1.2	118	0.054
Lincoln	6,138	12,302	22.6	124	1.2	149	0.024
Logan	5,288	12,277	19.2	123	1.2	147	0.028
Love	973	3,583	17.9	60	1.2	71	0.073
Major	1,520	3,855	20.2	68	1.2	81	0.054
Marshall	1,311	7,389	15.7	73	1.2	88	0.067
Mayes	2,728	15,470	14.8	106	1.3	138	0.051
McClain	3,700	9,300	21.7	106	1.2	127	0.034
McCurtain	4,545	13,828	18.9	124	1.2	148	0.033
McIntosh	2,019	10,708	21.8	91	1.2	109	0.054
Murray	504	5,742	13.3	48	1.3	62	0.124
Muskogee	1,256	28,882	15.9	78	1.2	93	0.074
Noble	610	4,894	26.2	52	1.2	62	0.102
Nowata	281	4,534	18.8	36	1.2	44	0.155
Okfuskee	936	4,894	23	62	1.2	74	0.079
Oklahoma	21,092	279,340	14.4	312	1.3	406	0.019
Okmulgee	482	16,431	18.6	48	1.2	58	0.120
Osage	2,203	18,196	17.2	98	1.2	118	0.054
Ottawa	2,082	14,064	24	94	1.2	113	0.054
Pawnee	1,653	7,407	42	80	0.6	48	0.029
Payne	3,068	27,381	16	117	1.2	140	0.046
Pittsburg	1,426	19,433	21.8	81	1.2	98	0.068
Pontotoc	1,574	15,094	18.4	84	1.2	101	0.064
Pottawatomie	8,237	24,528	18.4	165	1.2	198	0.024
Pushmataha	1,694	5,190	17	76	1.2	91	0.054
Roger Mills	880	2,048	33.3	50	0.6	30	0.034
Rogers	811	21,455	16.8	62	1.2	75	0.092
Seminole	2,921	11,404	19.9	104	1.2	125	0.043
Sequoyah	2,010	14,314	18.4	93	1.2	112	0.055
Stephens	3,593	19,675	16.6	121	1.2	145	0.040
Texas	1,558	7,328	23.9	78	1.2	94	0.060
Tillman	403	4,704	24.2	43	1.2	52	0.128
Tulsa	1,827	227,834	13.6	95	1.3	124	0.068
Wagoner	1,252	19,262	16.1	77	1.2	92	0.073
Washington	293	21,707	15.3	38	1.2	46	0.156
Washita	1,200	6,101	27.3	69	1.2	83	0.069
Woods	573	4,782	23.8	50	1.2	60	0.105
Woodward	1,473	8,512	19.8	78	1.2	94	0.064

[(a)] The standard sample error, SE(X), is calculated as $SE(X) = F\sqrt{5X\left(1 - \frac{X}{N}\right)}$, where X is the number of wells, N is the number of housing units, and F is the percent-in-sample factor for the source of water census question (US DOC, 1993, page C-10).

[(b)] For source of water, the factor, F, is 1.3 for percent-in-sample of 15% or less; 1.2 for percent-in-sample of 15% to 30% and 0.6 otherwise (US DOC, 1993, page C-11).

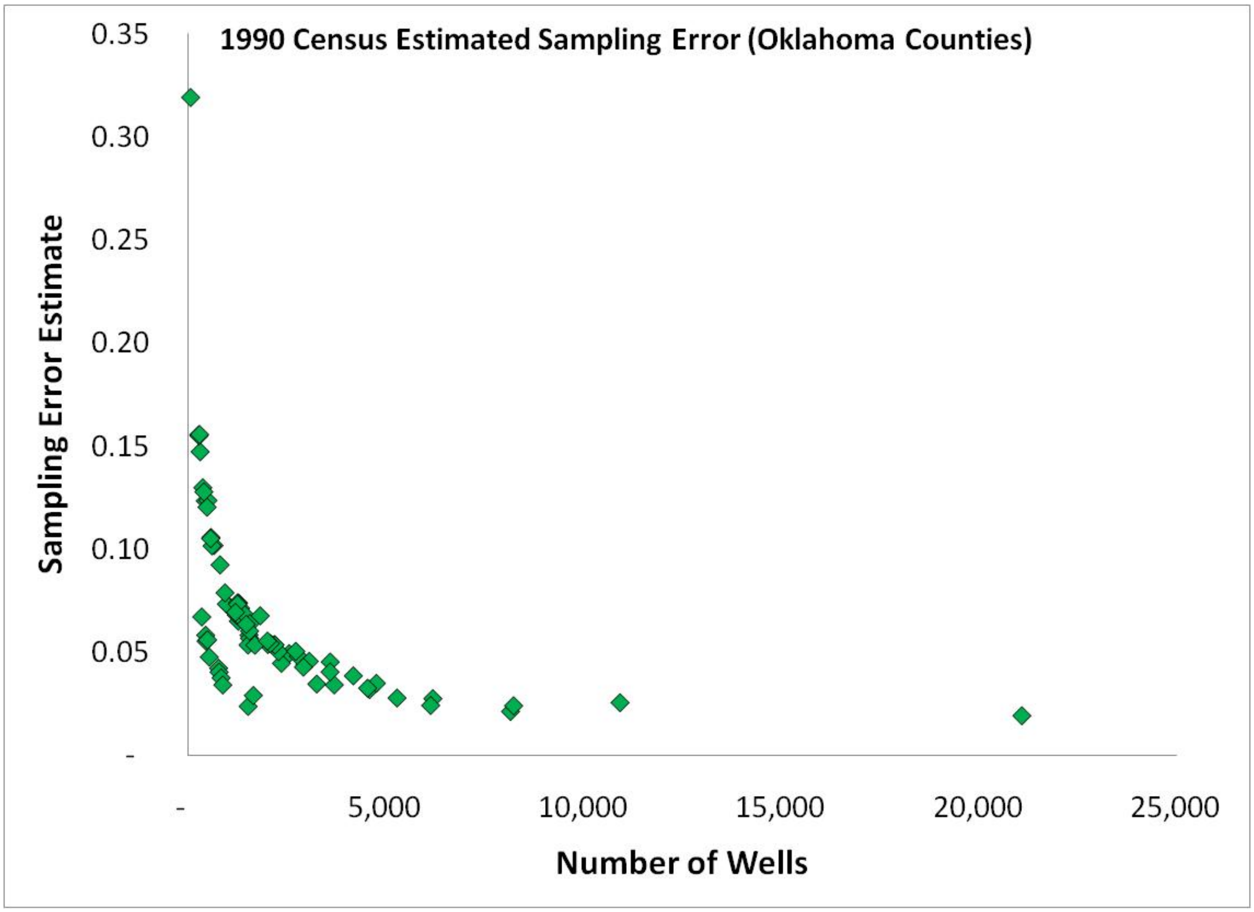


Figure 7. Standard sampling error estimates for Oklahoma counties determined from equations presented below Table 1 .

The Census Bureau attempts to control additional non-sampling errors that might result from respondent, enumerator, and processing errors, as well as missed households and nonresponse (US DOC, 1993). Non-sampling errors, if random, increase the variability and are reflected in the standard sampling error (US DOC, 1993). Using the 9% error calculated from the first test as a bound, the actual number of wells in use in Oklahoma in 1990 could have ranged from 161,000 to 193,000. Despite these errors, the estimates are an order-of-magnitude above the number of reported wells for 1990 (15,042), so the inference from the census provides a suitable basis for the estimates updated to 2000 and 2010.

As a check on the net housing unit method, census data in ten-year increments were used to estimate well use in Oklahoma counties for 1970, 1980, and 1990 using the net housing unit method. The estimates were compared against the census-reported values (Figure 8 to Figure 13) as a means to assess the NHU method's viability. The highest statewide errors occurred for the 1970 (26.8%, Figure 8 and Figure 9) and 1980 (27.6%, Figure 10 and Figure 11) estimates. The error dropped to 5.7% for the 1990 estimate (Figure 12 and Figure 13). Given that the key estimated factor is the ratio of well use to public supply, the lower 1990 estimate of 5.7% indicates that the ratio remained relatively constant from 1980 to 1990. The result is explained by data from OWRB (1998), which show ten or more rural water systems were added in Oklahoma each year between 1962 and 1974, implying a shift from wells to public supplies between 1960 and 1980. The decade between 1985 and 1995 typically showed less than five rural water districts added in each year, implying a smaller shift to public water supplies (Figure 14) and thus smaller error for the 1990 result (Figure 12 and Figure 13).

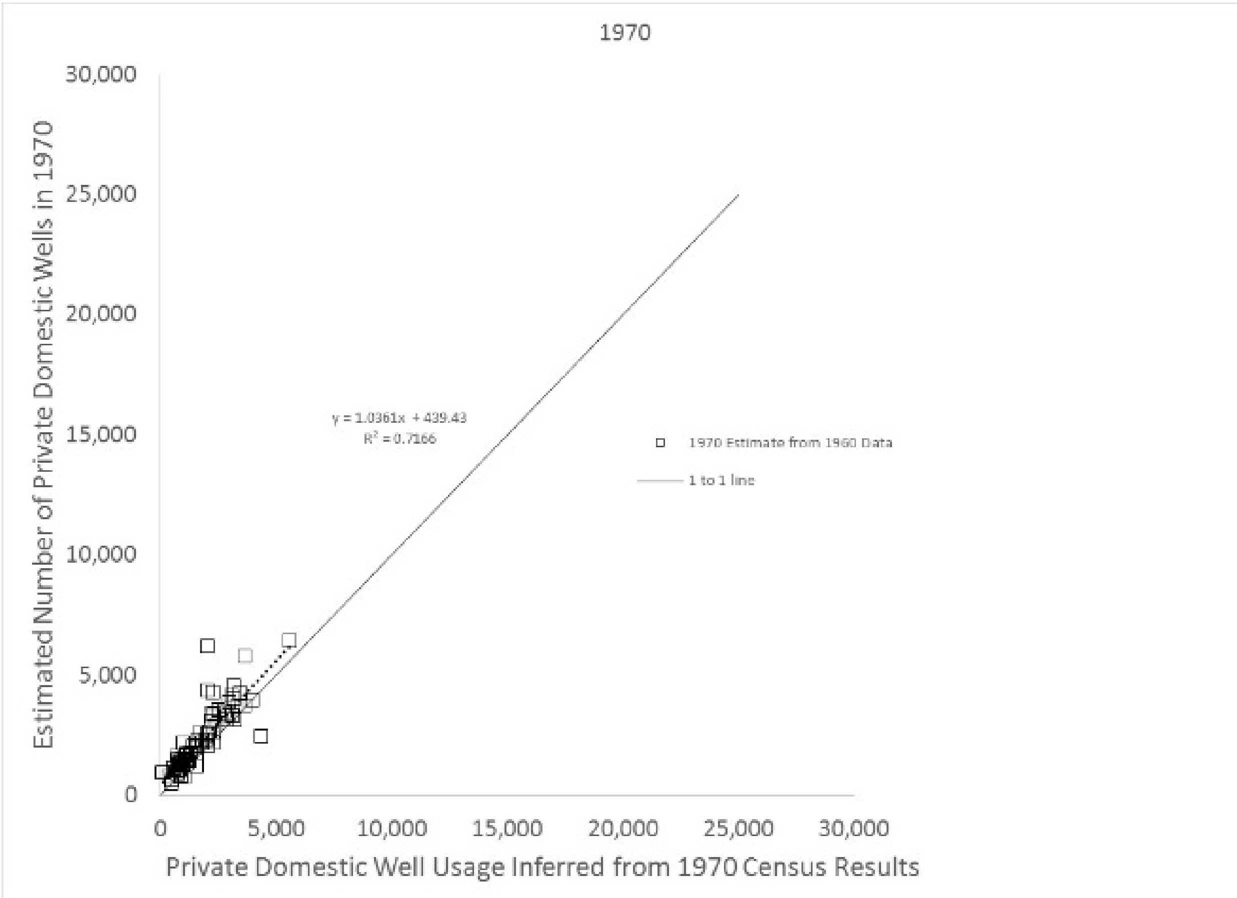


Figure 8. Comparison of county-level estimated private domestic well use and that inferred from the U.S. Census for 1970. Because the water supply question was not asked in places of greater than 50,000 in population in 1960, the 1970 estimates exclude three of Oklahoma's 77 counties, namely Comanche, Oklahoma, and Tulsa.

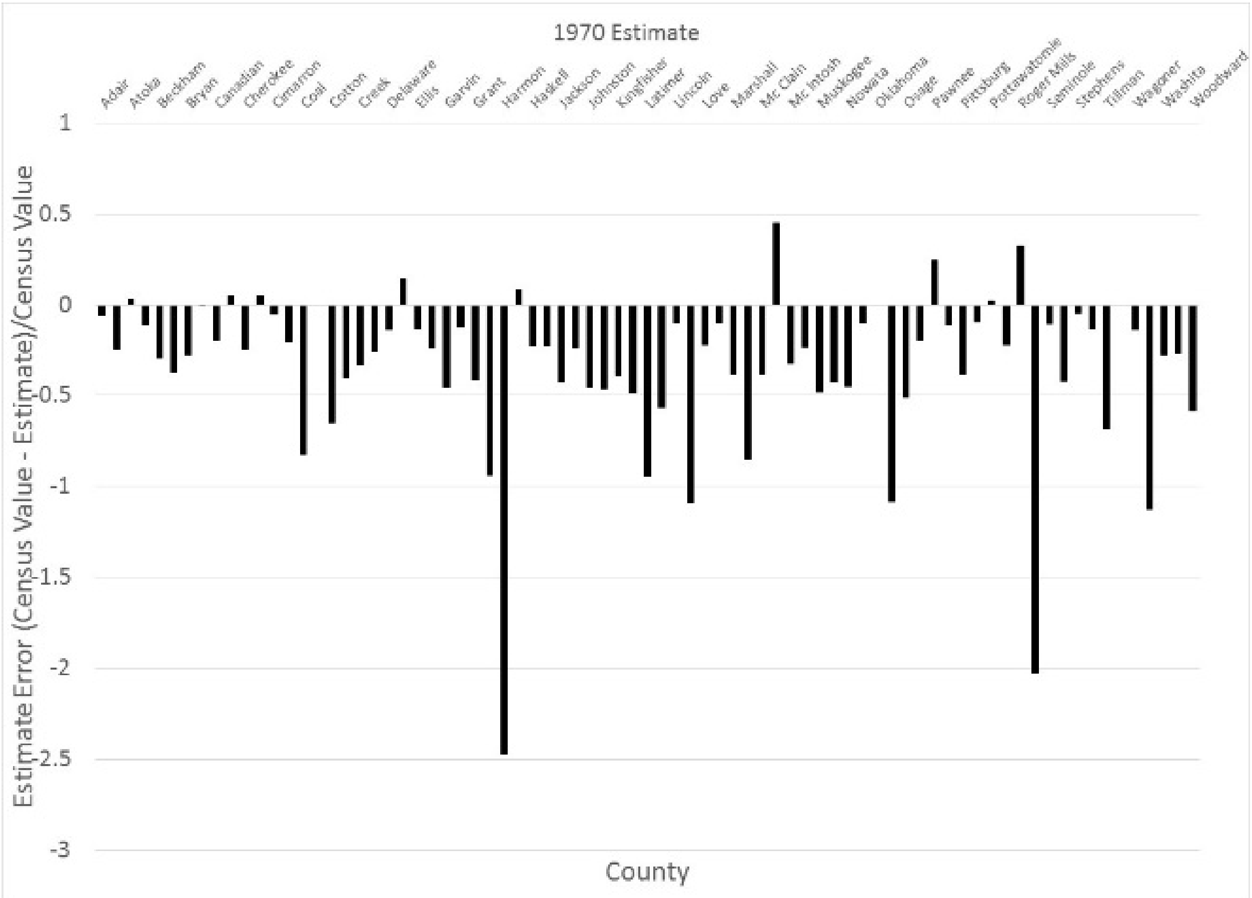


Figure 9. Error estimates (Census Value – Estimate)/Census Value for county-level PDW estimates given by county for 1970.

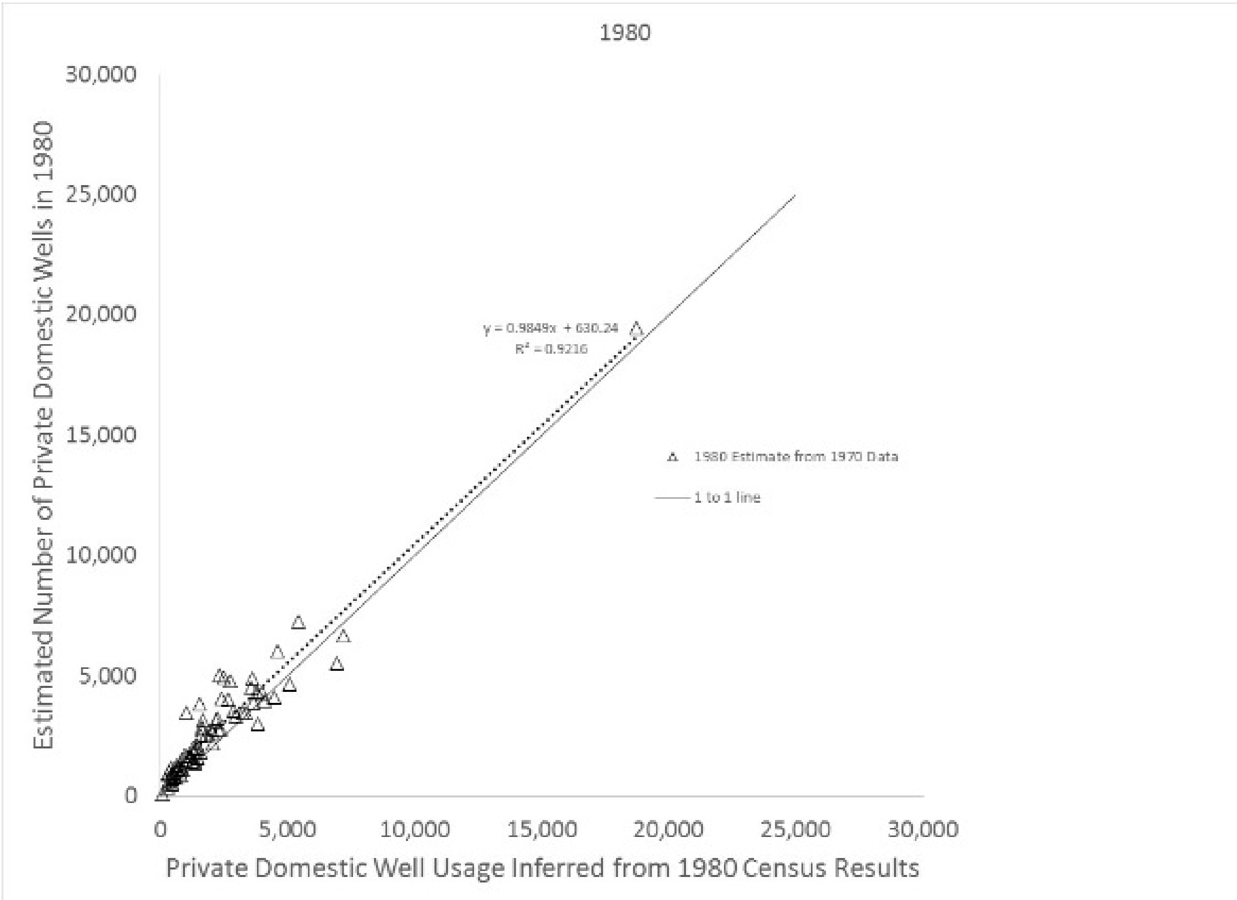


Figure 10. Comparison of county-level estimated private domestic well use and that inferred from the U.S. Census for 1980.

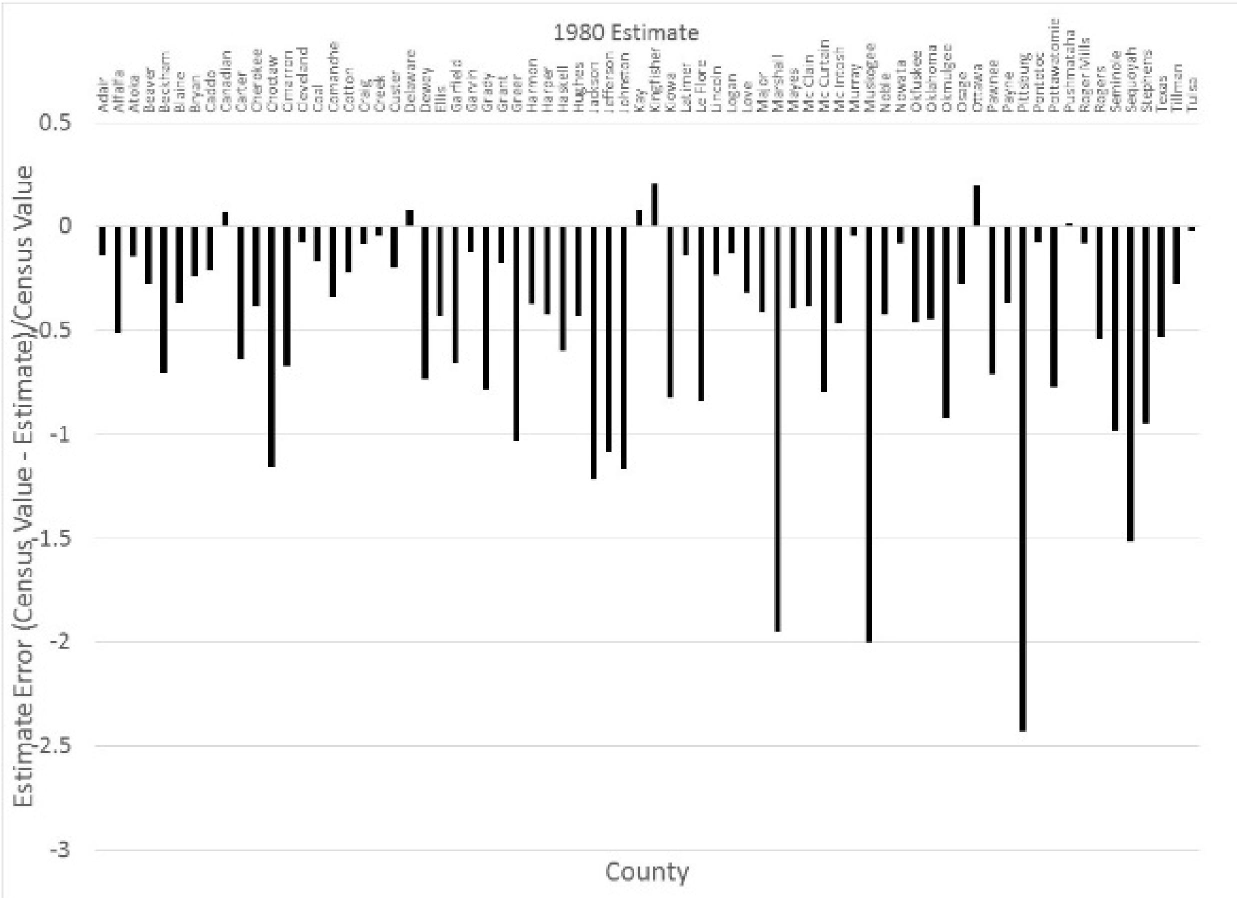


Figure 11. Error estimates (Census Value – Estimate)/Census Value for county-level PDW estimates given by county for 1980.

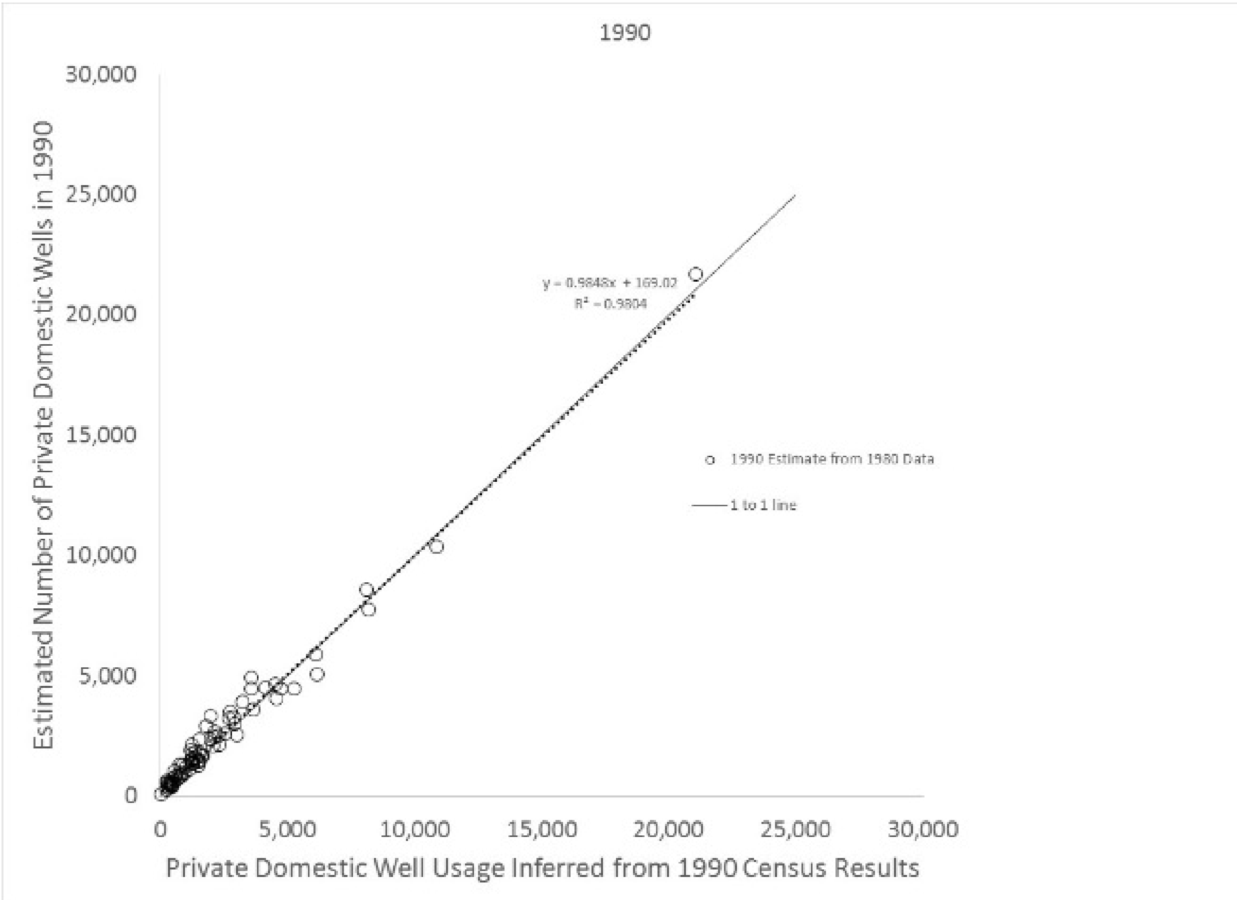


Figure 12. Comparison of county-level estimated private domestic well use and that inferred from the U.S. Census for 1990.

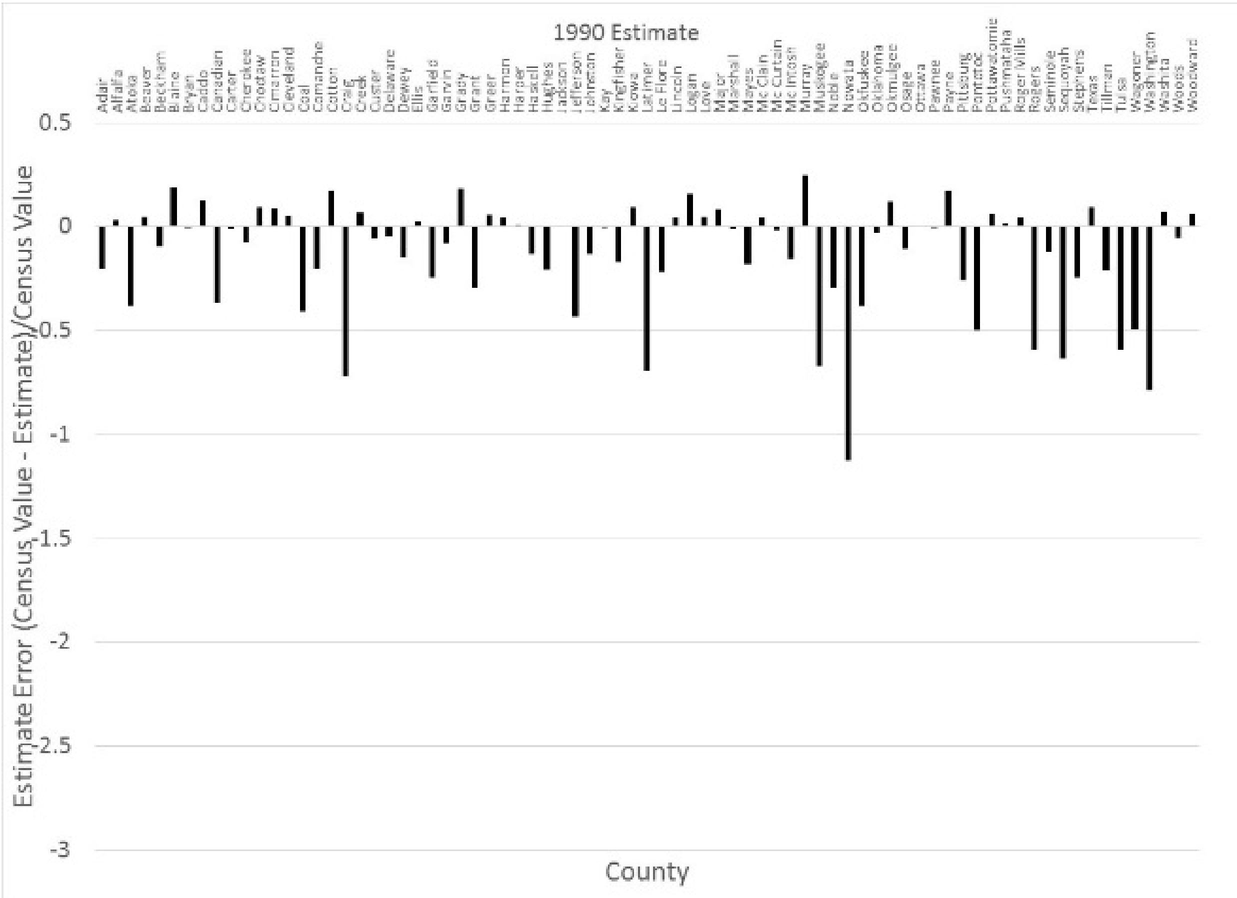


Figure 13. Error estimates (Census Value – Estimate)/Census Value for county-level PDW estimates given by county for 1990.

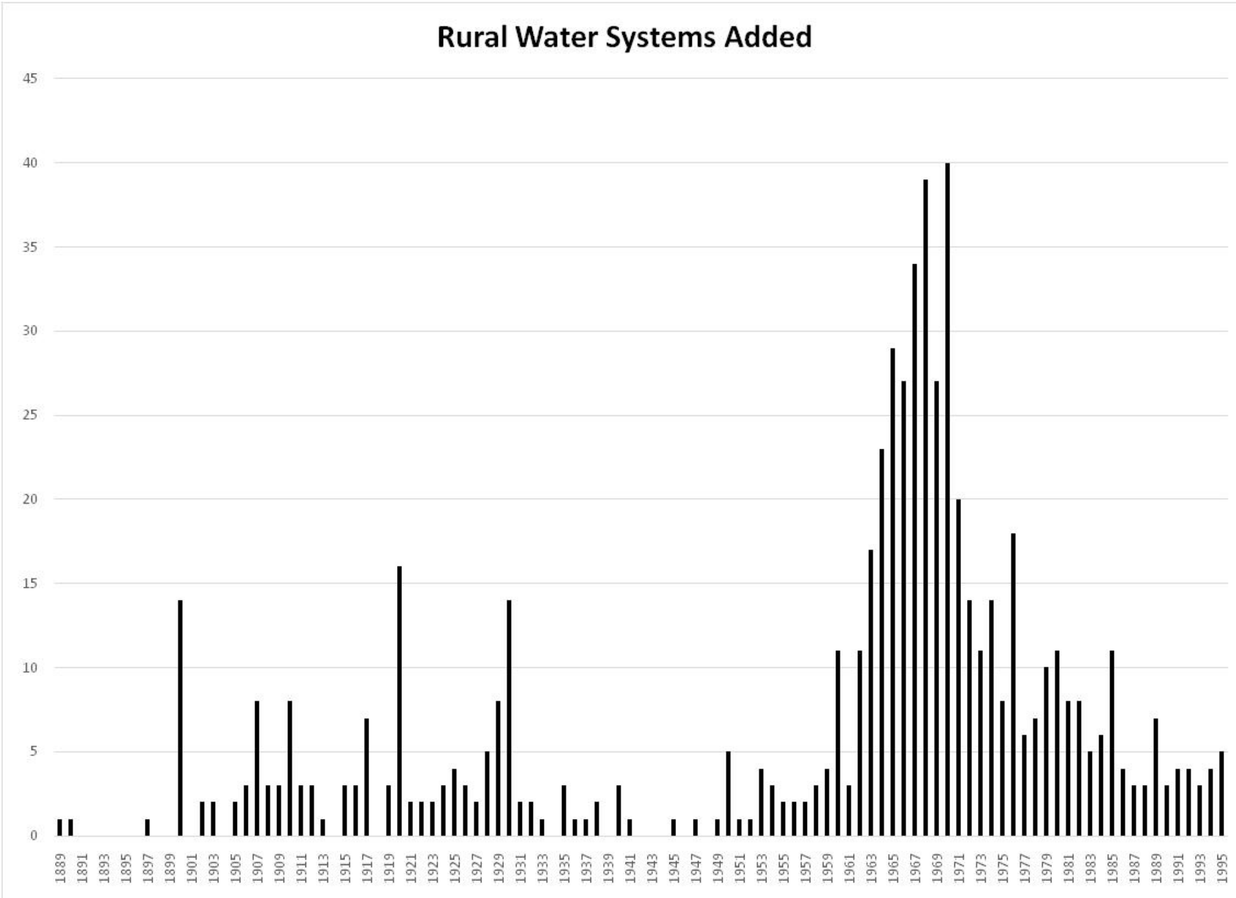


Figure 14. Rural water districts added in Oklahoma 1889-1995 (data from OWRB, 1998).

State-Wide Inferences

In 1990, public or private water systems were reported as the source of water for over 1.2 million housing units in Oklahoma (Table 2), which were located both in urban and rural areas. Individual drilled or dug wells were reported for about 177,000 housing units in Oklahoma, the majority of which were located in rural areas. However, more than 30,000 housing units were reported as using individual wells in urban areas. In total, well use constituted 12.6% of Oklahoma water supply on a housing unit basis. When displayed on a census block group spatial basis, the 1990 inferred densities of well usage showed high levels in areas surrounding Oklahoma City and in northeastern Oklahoma (Figure 3) for reasons discussed below. The census results illustrate the limitations of the well reports, because they began in the mid-1980s (OACR, 2015), the reported wells undercount the total. A cumulative total of 15,042 were reported through 1990, which is 8.5% of the census inference of 177,074 (Figure 15). Because reporting of well logs is now required, undercounting since the 1980s should be less but this presumption requires testing (see section "City and Neighborhood Analysis" below).

Table 2. Oklahoma water sources from the 1990 census (U.S. DOC, 1993).

Water Supply	***Total***	***Fraction of Total***	***Urban***	***Rural***
Public or private water system	1,223,121	0.8696	928,727	294,394
Total well use	177,074	0.1259	30,259	146,815
Individual drilled well	163,916	0.1165	28,026	135,890
Individual dug well	13,158	0.0094	2,233	10,925
Other Source	6,304	0.0045	556	5,748

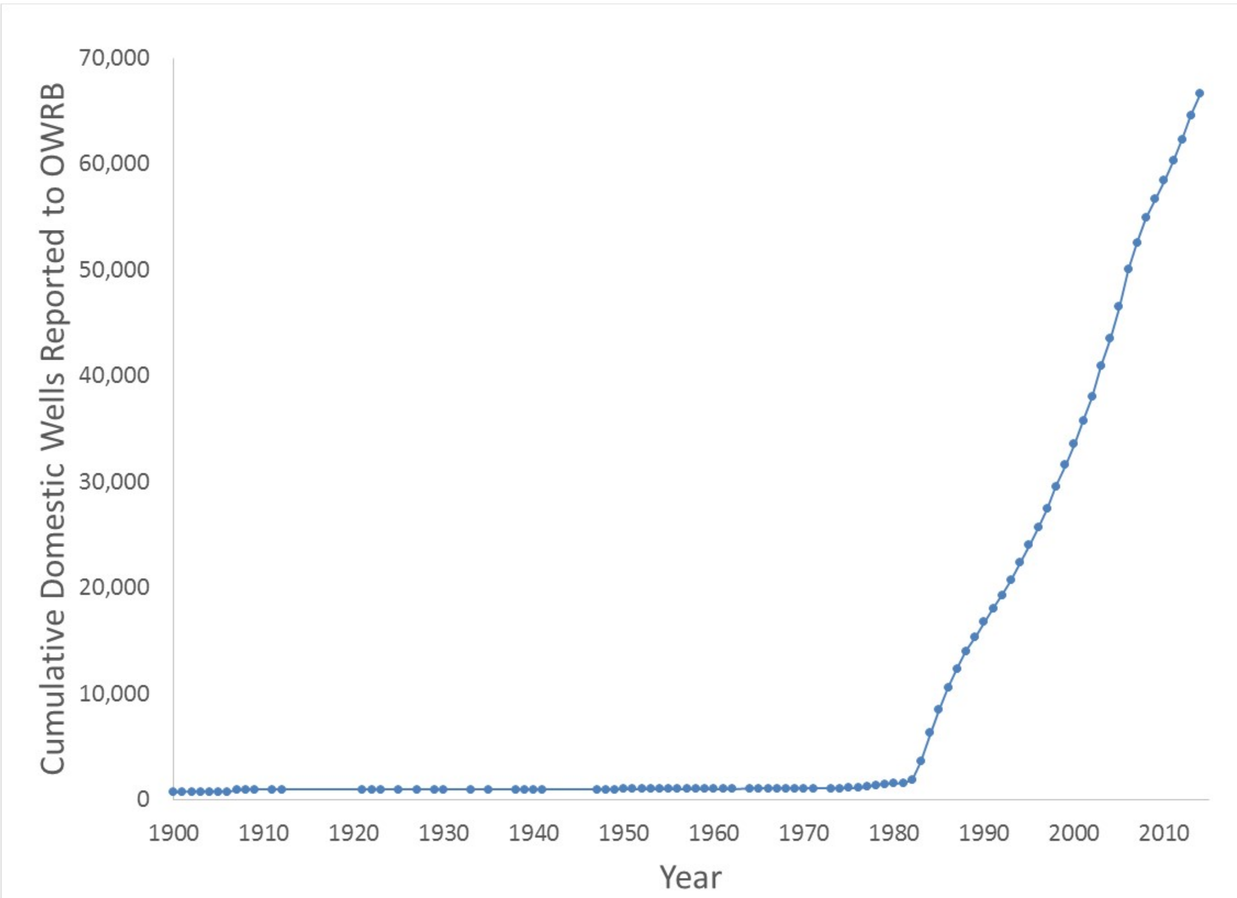


Figure 15. Cumulative number of domestic wells reported to the Oklahoma Water Resources Board.

County-level Estimates

Based on data aggregated to the county level, the population, number of housing units, and estimated number of wells all increased in Oklahoma from 1990 to 2010 (Table 3). The reported-wells estimate for well usage in 2010 (215,806) was less than that determined from simple addition of the 1990 Census inference and the raw number of wells reported between 1990 and 2010 (217,597), because of accounting for loss of housing units in the RW method. Based on the RW method results, the fraction of population relying on private wells (f_{pdw}) increased slightly from 0.1259 to 0.1297. The increase in reliance on private wells during this time period was greater than the increase in population (10.4% versus 9.7% and 11.3% versus 8.7%, Table 3).

Table 3. Housing unit, population and private domestic well characteristics for the state of Oklahoma

year	Housing Units	Population	RW Method Estimate	Direct Well Count	Housing Units/km^2	Wells/km^2	f_{pdw}	Population Using Wells	% inc in Population	%inc in Popluation Using Wells	Δf_{pdw}
1990	1,406,499	3,145,585	177,074[(a)]	177,074[(a)]	7.9189	0.9970	0.1259	396,020			
2000	1,514,400	3,450,654	191,796	193,290	8.5265	1.0799	0.1266	437,019	9.7	10.4	0.0060
2010	1,664,378	3,751,351	215,806	217,597	9.3709	1.2150	0.1297	486,406	8.7	11.3	0.024

[(a)] 1990 values are inferred from the 1990 U.S. Census.

High density of wells was found in the center of the state and along the border with Arkansas and Missouri (Figure 16) using the RW method. The highest densities occurred in Oklahoma County and adjoining Cleveland County, which also contains the extensive public water system of Oklahoma City (OKC 2014). The third highest well density was found in Delaware County in Northeastern Oklahoma, with a 2010 rural population of 29,103. Rural water districts covered around 24% of the county in the latest year data are available, 1995 (OWRB 2017). These three counties share the characteristics of availability of high quality ground water (Marcher and Bingham 1989, Figure 2), high or relatively high population, and limited coverage of public water supplies (OWRB, 1998 and Figure 17).

Summary statistics (Table 4) show an increasing mean well density from 1.138 wells/km^2 (1990 census inference) to values over 1.389 wells/km^2 for 2010, depending on the method used. Similarly, the county-level maximum density in 1990 was 11.489 wells/km^2, which increased to over 12 or 13 wells/km^2 for 2010 depending on method. As an example of the similarity of their results, the RW and NHU (with f_{pdw} updating to 2000) results for 2010 plotted close to a 1:1 line (Figure 18). The conceptual importance of updating the fraction of well usage, f_{pdw} , is illustrated by the changes in the mean from 0.1951 in 1990 to 0.2166 in 2010.

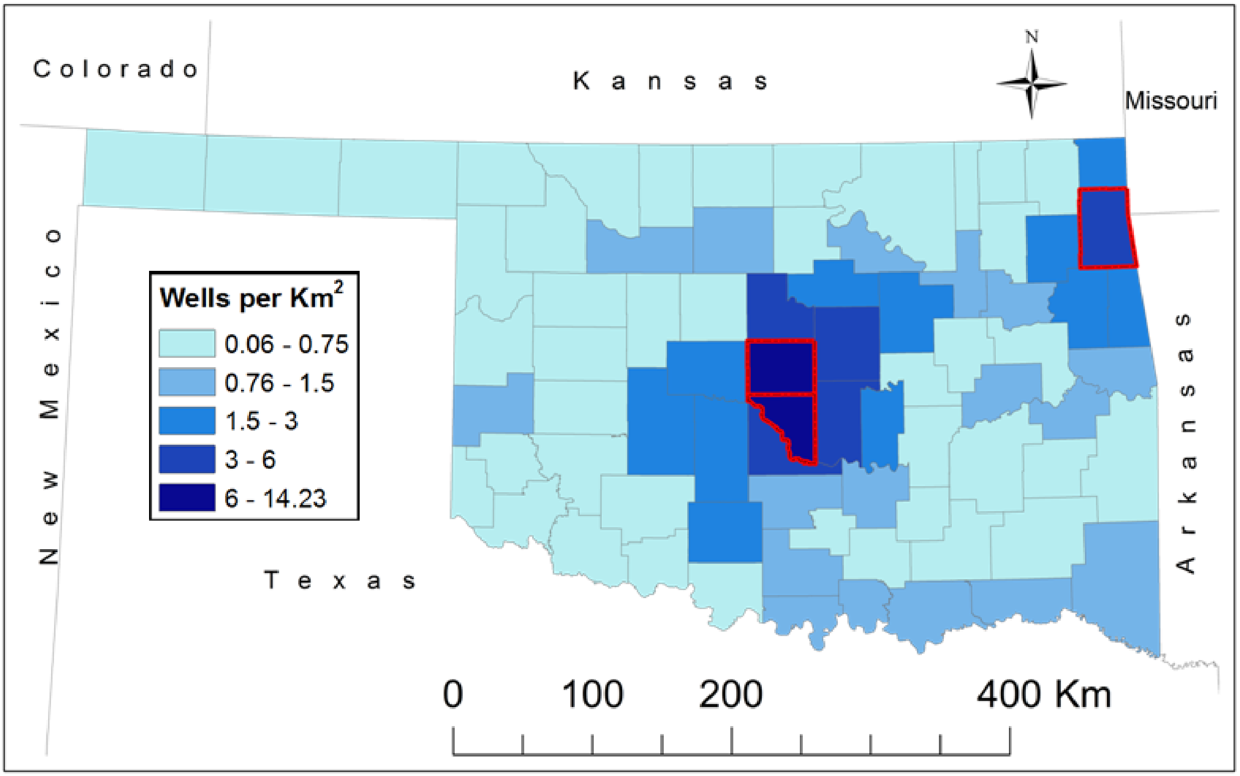


Figure 16. Reported-wells estimate of private domestic well density for 2010 on a county-wide spatial scale. Oklahoma (top) and Cleveland (bottom) counties in the center of Oklahoma, and Delaware County on the border with Missouri and Arkansas had the highest estimated well density in the state.

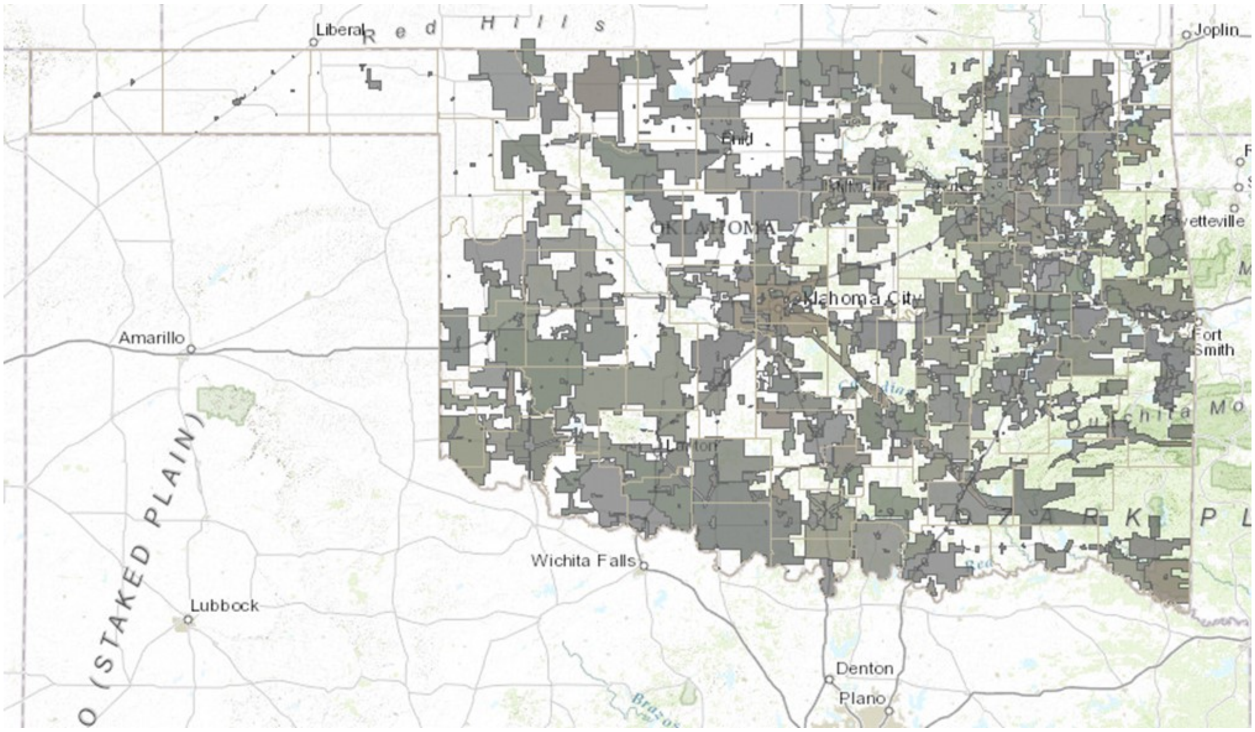


Figure 17. Approximate service areas of public water systems in Oklahoma (Oklahoma Water Resources Board, 1998).

Table 4. Summary statistics for private domestic well density estimates (wells per km^2) from the 1990 census, reported wells, and net housing unit estimates for the 77 counties, 1,046 census tracts, and 2965 census block groups of Oklahoma.

Estimate	*Minimum*	*Q1*	*Median*	*Q3*	*Maximum*	*IQR*[(a)]	*Mean*	*Variance*
			County Scale (median size 2078 km^2)					
Dens 90	0.0489	0.301	0.592	1.313	11.489	1.013	1.138	2.763
RW 2000	0.0571	0.327	0.629	1.357	12.249	1.030	1.233	3.275
RW 2010	0.0636	0.368	0.700	1.461	14.232	1.094	1.388	4.423
NHU 2000	0.0449	0.296	0.594	1.453	12.134	1.157	1.254	3.509
NHU 2010	0.0421	0.295	0.631	1.617	13.154	1.322	1.389	4.584
NHU 2010 f_{2000}	0.0396	0.292	0.629	1.583	13.170	1.290	1.372	4.472
NHUGS 2000	0.0447	0.316	0.604	1.398	11.674	1.082	1.254	3.328
NHUGS 2010	0.0435	0.289	0.616	1.519	12.463	1.231	1.327	3.934
			Census Tract Scale (median size 12.40 km^2)					
Dens 90	0.00	0.00	0.492	2.382	81.111	2.382	3.083	61.395
RW 2000	0.00	0.000830	0.618	2.556	81.691	2.382	3.196	62.491
RW 2010	0.00	0.0652	0.747	2.800	77.742	2.735	3.494	70.072
NHU 2000	0.00	0.00	0.535	2.704	114.178	2.704	3.901	105.340
NHU 2010	0.00	0.00	0.652	3.153	113.334	3.153	4.873	160.029
NHU 2010 (f_{2000})	0.00	0.00	0.641	3.130	114.132	3.130	4.607	138.342
			Census Block Group Scale (median size 2.66 km^2)					
Dens 90	0.00	0.00	0.276	2.082	143.454	2.082	3.465	106.146
RW 2000	0.00	0.00	0.376	2.322	145.071	2.322	3.575	105.966
RW 2010	0.00	0.00	0.478	2.739	145.313	2.739	3.887	113.597
NHU 2000	0.00	0.00	0.274	2.373	191.630	2.373	4.258	157.943
NHU 2010	0.00	0.00	0.282	2.762	401.921	2.762	5.403	295.804
NHU 2010 (f_{2000})	0.00	0.00	0.281	2.700	200.703	2.700	5.024	215.554

[(a)] IQR = interquartile range, Q3 – Q1

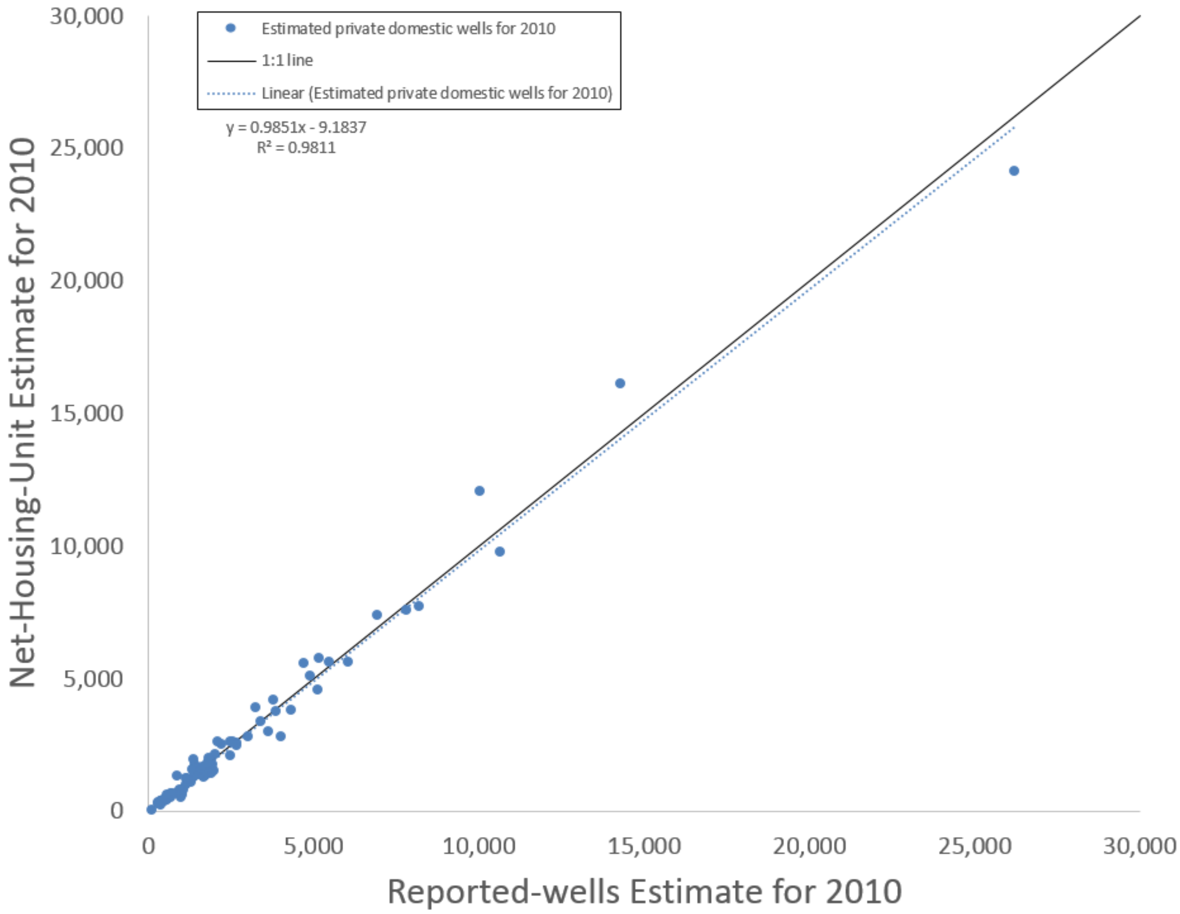


Figure 18. County-level predicted private domestic well use for 2010 from housing unit increase compared against predicted well use from well logs reported to the OWRB.

Using USGS domestic self-supplied water-use estimates to update f_{pdw} (rather than the reported well logs) gave results which were similar to the RW method results. The USGS estimates were based on available data which differed among counties (Hutson 2007). The estimates show fluctuating levels of well use over the period 1985 to 2010 (Figure 19 for five selected counties and the Appendix for all Oklahoma counties). In particular, several counties showed large increases followed by large decreases in public water usage (i.e., Adair, Hughes, Latimer, Roger Mills, and Washita), which suggests further refinement is needed for county level estimates of well usage (Figure 19).

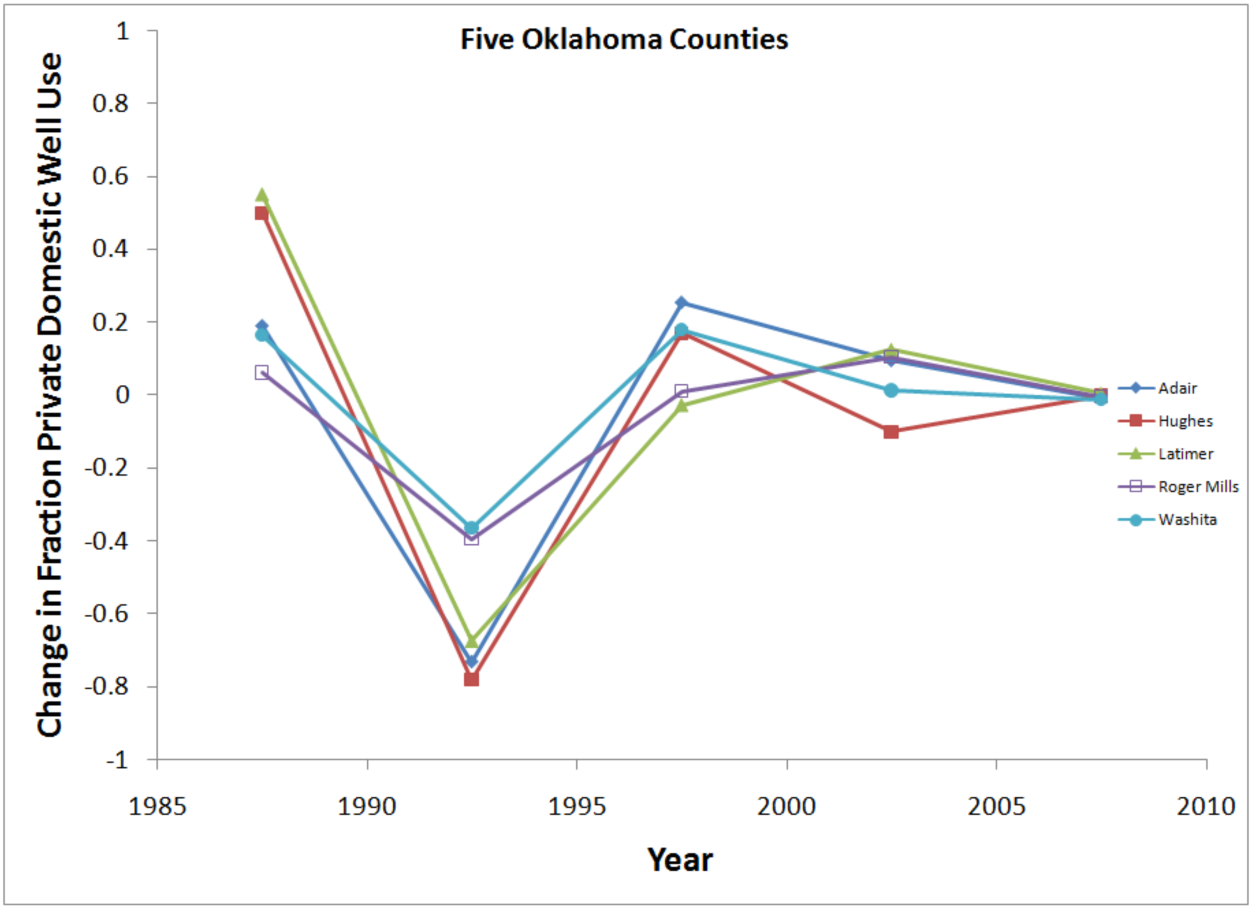


Figure 19. Changes in fraction of private domestic well use from USGS water supply data for 1985 to 2010 for five Oklahoma Counties. Results for other Oklahoma counties appear in the Appendix.

Despite differences in approach among the methods, statistical comparison (Table 5) showed no statistically significant differences between the 1990 census inference and any method results, the variants on the NHU method and the RW method, nor the fraction of private well use.

Table 5. Statistical comparison of 1990 private domestic well density and estimates made the RW and NHU methods. Bold italic values differ statistically at 0.05 P value in the table. Quantity names are as follows: Dens 90 = inference from 1990 census; RW 2000 = reported-wells result for 2000; RW 2010 = reported wells result for 2010; NHU 2000 = net housing unit result for 2000; NHU 2010 = net housing unit result for 2010; NHU 2010 (f_{2000}) = net housing unit result for 2010 with the fraction of private domestic well use (f_{pdw}) updating from RW 2000 result; NHU USGS 2000 = net housing unit result for 2000 with f_{pdw} updating from USGS results; and NHU USGS 2010 = net housing unit result for 2010 with f_{pdw} updating from USGS results.

Test Quantity 1	***Test Quantity 2***	***P Value***		
		Counties	***Census Tracts***	***Census Block Groups***
		1990 Census Inference versus 2000 and 2010 estimates		
Dens 90	RW 2000	0.6003	0.1409	***0.0177***
Dens 90	RW 2010	0.2799	***0.0017***	***<0.0000***
Dens 90	NHU 2000	0.8171	0.3688	0.2273
Dens 90	NHU 2010	0.5804	0.1082	***0.0360***
Dens 90	NHU 2010 (f_{2000})	0.8708	0.0752	0.2216
Dens 90	NHU 2000 (USGS)	0.6053	--	--
Dens 90	NHU 2010 (USGS)	0.6857	--	--
		RW method versus NHU method		
RW 2000	NHU 2000	0.8301	0.5963	0.2748
RW 2010	NHU 2010	0.6725	0.1872	***0.0177***
RW 2010	NHU 2010 (f_{2000})	0.6359	0.2190	***0.0164***
		NHU method with and without fraction well use updating		
NHU 2010	NHU 2010 (f_{2000})	0.9165	0.8871	0.9854
		Fraction of Private Domestic Well (f_{pdw}) Use		
f_{pdw} 1990	*f_{pdw} 2000*	0.6489	0.9294	***0.0005***
f_{pdw} 1990	*f_{pdw} 2010*	0.5295	0.6774	***<0.0001***
f_{pdw} 2000	*f_{pdw} 2010*	0.8087	0.7255	0.1551

Census Tract Scale Estimates

At the census tract scale, the mean well densities increased from 3.083 in 1990 to 4.873 wells/km^2 for 2010 depending on method (Table 4). Differing from the counties, some census tracts had no wells, thus densities of 0.0 wells/km^2, but all counties had at least a few wells. Reflecting the smaller spatial basis of the census tracts (170 km^2 versus 2,307 km^2), the maximum density was as high as 114 wells/km^2, which is a value much higher than seen in any entire county. The counties can contain locales supplied by urban and rural public water, or contain open land with no need for private wells, so they have both higher and lower extremes. By design the census tracts are conceptually more homogeneous. As seen in the statistical results, however, the only statistically significant difference is between the 2010 RW results and the 1990 census inference. Although generally corresponding to the county-level result and on the eastern boundary (Figure 20), the smaller size of the census tracts allows sub-county heterogeneity to appear, in counties showing either high or low well density estimates (Figure 20, left).

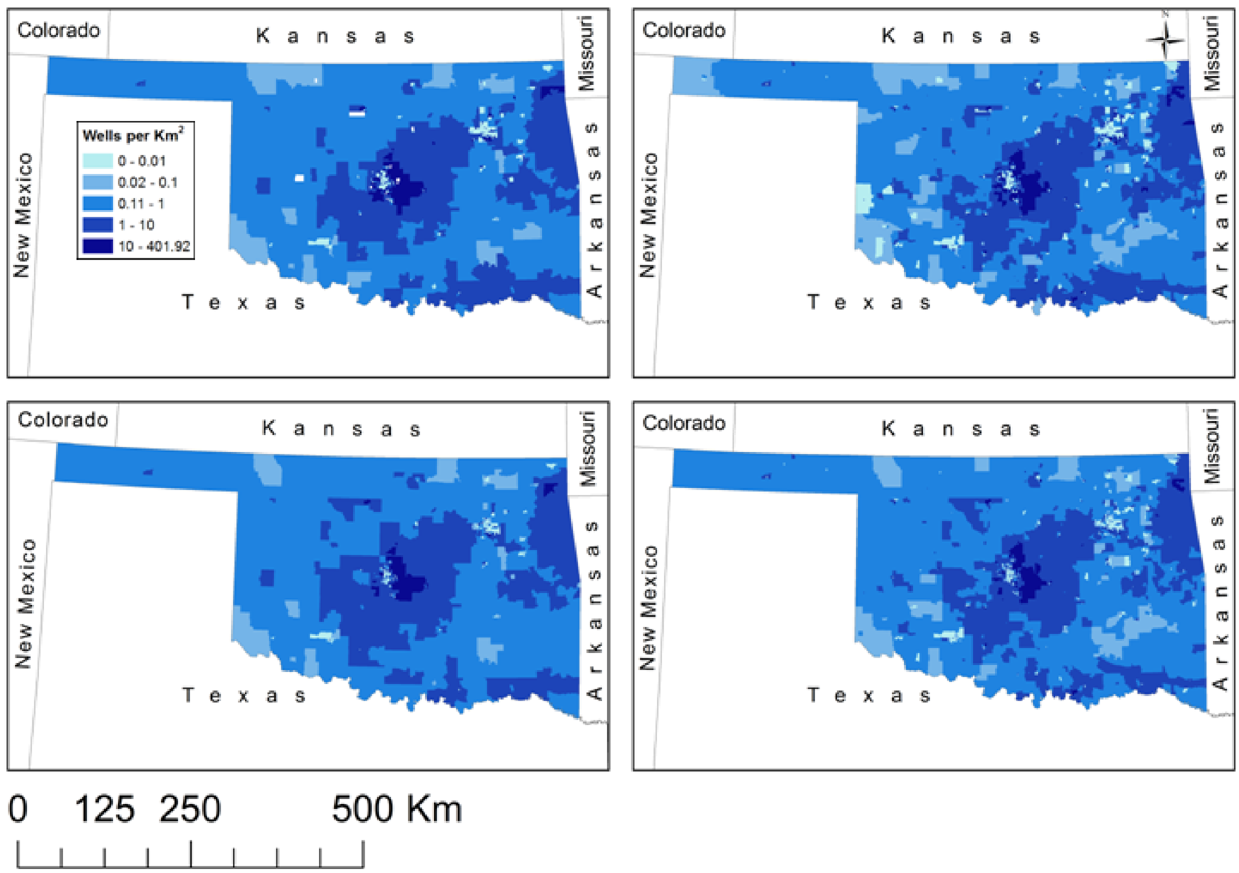


Figure 20. Net housing unit (NHU) method (top), and reported-wells (RW) method (bottom) 2010 results for census tracts(left) and census block groups (right) in Oklahoma.

Census Block Group Scale Estimates

At the smaller census block group scale (mean 2010 land area of 60 km^2), the mean well density started at 3.465 wells/km^2 in 1990 and increased to as much as 5.403 wells/km^2 in 2010, depending on method (Table 4). Likewise, the maximum density went from 143.5 wells/km^2 in 1990 to as much as 401.9 wells/km^2 in 2010. Similar to the census tract scale, there were census block groups that contained no wells. At this spatial scale, the RW method estimates for 2000 and 2010, and the fraction of well use differed statistically from the 1990 census inference (Table 5).

At the census block group level, small-scale variability increased over the census tract results and (Figure 20, right). The RW method generated lower estimates than the NHU in 37% of the census block groups with no f_{pdw} updating and 38% with f_{pdw} updated to 2000. Higher NHU results were evident by both the visible higher densities and more widespread distribution of high densities in the NHU results (Figure 20, right).

The estimated difference between the 1990 well density and the RW 2010 estimates showed large areas with 10% to 100% increases (Figure 21). This result implies that the fraction of well use increased in many areas of the state including the central and northeastern Oklahoma (Figure 22), the area of highest well usage. At the census block group level the changes in well use both in numbers and in the fraction of households using private wells were statistically significant (Table 5). This result reflects that the changes are occurring on a small spatial scale that is better represented by the block group estimates. This effect can be seen in the Oklahoma City area, where some census block groups showed strong increases and others showed strong decreases. These are associated with expansion of cities surrounding Oklahoma City which have relied simultaneously on both public and private water supplies.

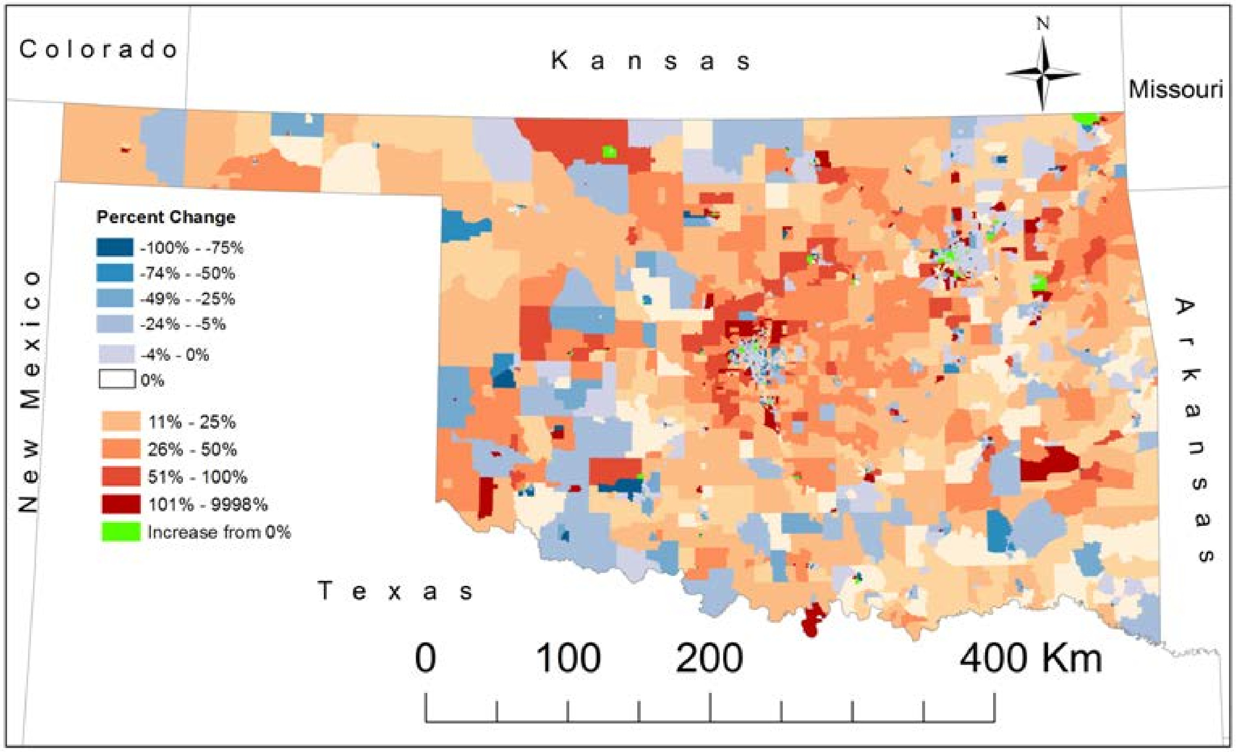


Figure 21. Percent change in estimated well density 1990 to 2010 using the reported well log (RW) method on the census block group level.

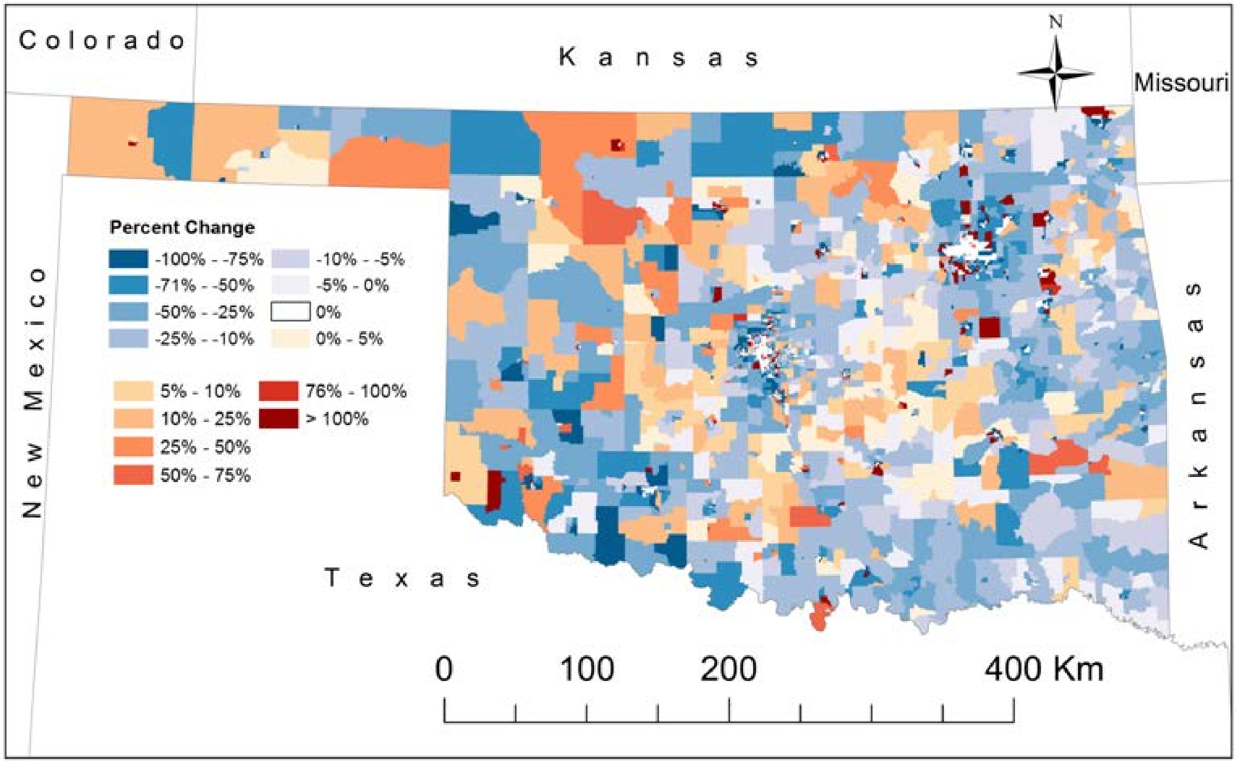


Figure 22. Estimated change in fraction of well to total water supply from 1990 to 2010 on the census block group level.

City and Neighborhood Scale Analysis

Example Cities without Public Water Supplies

Analysis at the city- and neighborhood-level provides insight into the reasons for the observed patterns and a further check on the accuracy of reported data. Three communities were identified in Oklahoma County with no public water supply systems and with residents reliant on wells: Forest Park, 2010 population 998; Lake Aluma, 2010 population 88; and Nicoma Park, 2010 population 2,393 (Figure *4* and Figure 17). Estimated densities of wells based on neighborhood counts of reported wells and existing residences resulted in higher well density from the corresponding census block group 2010 estimates for the RW method for two reasons (Table 6.)

First, property records show that houses were built in Forest Park and Nicoma Park prior to the well-reporting requirement and few reported wells were expected. Although the RW method is dependent on the reported well data, it resulted in high well density because of its basis in the 1990 census results which had already identified these areas as reliant on wells. Secondly, these cities include only small undeveloped areas, so the city estimates were higher when based on the number of housing units, rather than the area. Dividing the neighborhood count by housing units by the larger unit (county, census tract, and census block group) well density gives an indication of how much higher the well densities within the cities with no public water supplies can be compared with the larger land unit; the median result was 7.63 times larger for counties, 2.60 times larger for census tracts, and 2.19 times larger for census block groups (Table 6.)

Table 6. County, census tract, census block group reported-wells method, and neighborhood-count estimates of private domestic well usage for the cities of Lake Aluma, Forest Park, and Nicoma Park, all of which have no public water supply system.

Location	Well density (wells/km²)					Count by Housing Units Divided by Larger Unit Well Use		
	Wells Added Method 2010 Estimate			Neighborhood Counts		County	Census Tract	Census Block Groups
	County	Census Tract	Census Block Groups	by wells reported	by housing units			
Lake Aluma								
Whole	14.3	41.9	36.3	--	--			
Lake Aluma Dr (residences only)	14.28	41.9	36.3	14	98	6.86	2.34	2.70
Lake Aluma Dr (whole area)	14.28	41.9	36.3	7	48	3.36	1.15	1.32
Forest Park								
Whole	14.3	41.9	36.3	--	--			
			97.9					
N. Bryant and NE 50th ST	14.28	41.9	28.8	6	63	4.41	1.50	2.19
NE 36TH and N Coltrane (1st neighborhood)	14.28	41.9	36.3	13	109	7.63	2.60	3.00
NE 36TH and N Coltrane (2nd neighborhood)	14.28	41.9	36.3	25	184	12.89	4.39	5.07
N Bryant and NE 36th ST	14.28	41.9	97.9	12	141	9.87	3.37	1.44
Nicoma Park								
Whole	14.3	77.3	145.6	--	--			
			75.6					
			147.7					
			42.6					
			77					
NE 23rd and N. Westminster	14.28	77.3	147.7	15	213	14.92	2.76	1.44
			42.6					
			77					
Minimum for All Cities						3.36	1.15	1.32
Median for all Cities						7.63	2.60	2.19
Maximum for All Cities						14.92	4.39	5.07

Oklahoma City instituted an annexation policy to promote industrial development and to support Tinker Air Force Base, among other objectives (Oklahoman, 1959a, 1959b). Forest Park residents, however, resisted annexation by the City of Oklahoma City (Oklahoman 1956, 1957) and has remained independent (Figure 23). Forest Park was originally 73 ha (180 ac) in size, and annexed surrounding land to reach the size of 550 ha (1360 ac) (Everett, 2017a). Because the residences were built before the OWRB reporting requirements, few wells have been reported to the state. Well use is presumed from the 1990 census which indicated high density of private wells. A similar situation exists in Nicoma Park.

Nicoma Park is another small city with no public water system (Figure 24). Nicoma Park was a planned agricultural community whose purpose was to develop a "poultry colony" where residents would raise chickens to produce eggs on 1 to 5 acre lots under the supervision of an expert (Everett. 2017b). The project ended during the depression of the 1930s. The town persisted by residents finding employment in nearby Tinker Air Force Base (since the 1940s), automobile manufacturing, and other jobs in the Oklahoma City area (Everett, 2017b).

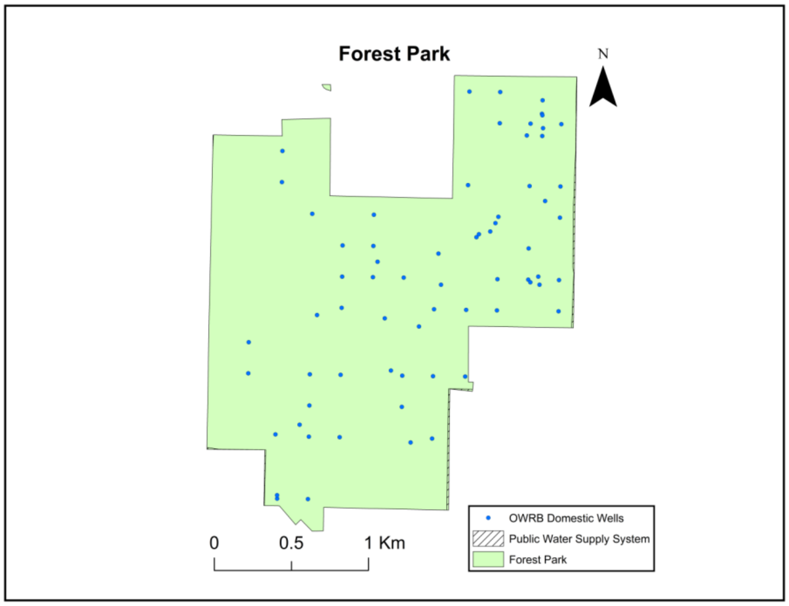


Figure 23. The City of Forest Park sits adjacent to Oklahoma City (Figure 4) and has no public water supply system.

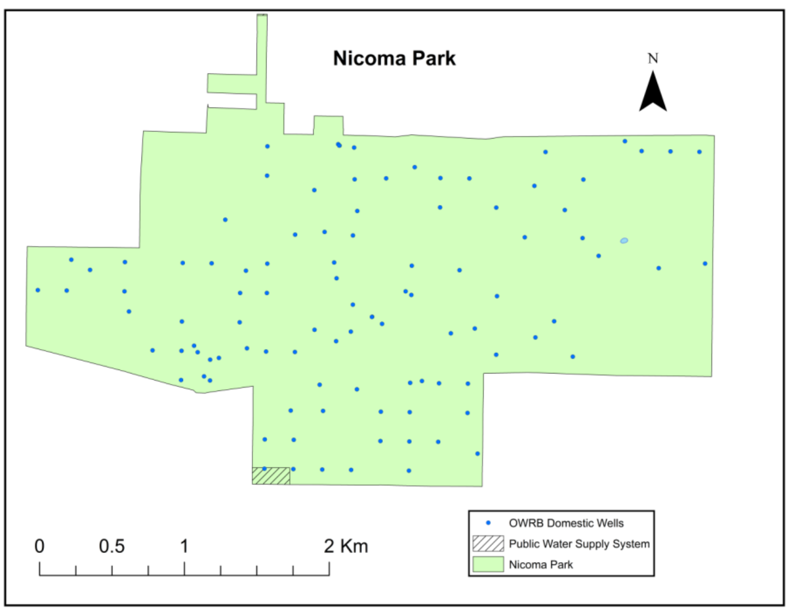


Figure 24. The City of Nicoma Park lies to the east of Oklahoma City (Figure 4) and has no public water supply system.

Individual Neighborhoods

Neighborhoods without public water supplies and recently-constructed homes were used independently to estimate well usage and to evaluate the completeness of well reports (Table 7). The developments ranged in size from 0.15 to 1.32 km^2, with median of 0.62 $km^{2.}$ The median fraction of wells reported, as required, to OWRB from 22 developments was 0.55, and the mean was 0.53, with range of 0.16 to 0.96. Adjacent subdivisions sometimes exhibited large differences in reporting. OWRB (2014) recognized the failure among some drillers to file required well completion reports. Similar to the communities discussed above, the estimates of well density on a neighborhood basis generally gave higher density than the 2010 RW method results for both the reported wells and the housing unit counts (Table 7). The higher densities obtained from neighborhood counts reflects higher density of housing units within the developments than in the undeveloped remainder of the areal unit (census block groups, census tracts, and county). Similar to the cities, pockets of higher reliance on wells can exist within larger units, and the median well densities can be 10.80, 11.24, and 9.36 times that of the county, census tract, or census block group (Table 7). The maximum well density can be as much as 500 times the census block group density for certain neighborhoods.

Table 7. Estimated private domestic well density for central Oklahoma neighborhoods, based on county, census tract, census block group, and neighborhood counts.

County	*Location*	*PDW density (wells/km²)*					*Estimated Fraction Reported wells[a]*	*neighborhood count by housing units/wells added estimate for counties, census tracts, and census block groups*		
		Wells Added Method 2010			*Neighborhood Count Method*					
		County	*Census Tracts*	*Census Block Groups*	*By reported wells*	*By housing units*		*County*	*Census Tracts*	*Census Block Groups*
Canadian	N Manning Rd & E0980, (SE 122 El Reno)	2.23	1.17	1.06	17	58	0.29	26.01	49.57	54.72
Canadian	SW 59TH and N. Czech Hall Rd	2.23	16.03	33.75	83	165	0.5	73.99	10.29	4.89
Canadian	NW Expressway and N. Frisco Rd	2.23	4.53	12.52	27	106	0.25	47.53	23.40	8.47
Cleveland	E. Indian Hills Rd & 168th Ave NE	10.24	20.5	22.91	69	110	0.63	10.74	5.37	4.80
Cleveland	S. Harrah Newalla Rd and SE 104TH St	10.24	20.5	22.91	69	97	0.71	9.47	4.73	4.23
Logan	S. Penn & W. Charter	3.6	17.21	18.62	95	191	0.5	53.06	11.10	10.26
Logan	NW 248th (Waterloo) & S. Portland Rd (Hwy 74)	3.6	3.85	4.39	137	257	0.53	71.39	66.75	58.54
Logan	S. Douglas & E. Waterloo	3.6	7.14	17.99	145	233	0.62	64.72	32.63	12.95
Oklahoma	SE 74TH and S. Choctaw	14.28	31.85	25.46	26	158	0.16	11.06	4.96	6.21
Oklahoma	E. Danforth and N. Douglas Rd	14.28	10.37	13.97	39	152	0.26	10.64	14.66	10.88
Oklahoma	E. Waterloo & N. Midwest Blvd.	14.28	10.37	13.97	56	215	0.26	15.06	20.73	15.39
Oklahoma	E. Covell and N. Douglas Blvd	14.28	10.37	13.97	52	158	0.33	11.06	15.24	11.31
Oklahoma	SE 15th and S. Dobbs Rd	14.28	31.85	24.91	39	109	0.36	7.63	3.42	4.38
Oklahoma	SE 89TH St and S. Indian Meridian Rd	14.28	31.85	25.45	46	80	0.58	5.60	2.51	3.14
Oklahoma	SE 44th & S Choctaw Rd	14.28	31.85	24.91	76	124	0.61	8.68	3.89	4.98
Oklahoma	E Hefner & N Air Depot Blvd	14.28	17.22	14.3	110	155	0.71	10.85	9.00	10.84

Oklahoma	E. Danforth and N. Midwest Rd	14.28	10.37	13.97	85	118	0.72	8.26	11.38	8.45
Oklahoma	Sorghum Mill Rd and N. Air Depot Rd	14.28	10.37	11.65	94	122	0.77	8.54	11.76	10.47
Oklahoma	S. Hiwassee Rd and SE 89TH St	14.28	14.66	19.57	55	70	0.79	4.90	4.77	3.58
Oklahoma	E. Waterloo & N. Midwest Blvd.	14.28	10.37	11.65	172	210	0.82	14.71	20.25	18.03
Oklahoma	SE 74TH and S. Choctaw	14.28	0.39	0.27	133	138	0.96	9.66	353.85	511.11
Oklahoma	Reduced size: E Danforth and N. Midwest Rd	14.28	10.37	13.97	78	112	0.7	7.84	10.80	8.02
Pottowatamie	New Hope Road and Walker Rd (NS 331)	5.22	13.26	12.95	14	50	0.28	9.58	3.77	3.86
Pottowatamie	River Rd & Rock Creek Rd	5.22	5.82	5.61	127	267	0.48	51.15	45.88	47.59
Minimum for all Neighborhoods								4.90	2.51	3.14
Median for all Neighborhoods								10.80	11.24	9.36
Maximum for all Neighborhoods								73.99	353.85	511.11

[a] The estimated fraction of reported wells is determined by dividing the number of reported wells by the number of residences.

Coexistence of Public and Private Water Supplies

In some cities, there appears to be significant co-existence of public and private water supplies. The city of Enid, Oklahoma (Figure 2 and Figure 25) is covered by an extensive public water system, yet has a large number of shallow (15 to 18m deep) wells. Local information and the observed response to a drought emergency declared in 2012, indicate that these wells are used for landscape maintenance, rather than primary domestic supply (Enid News 2012a and 2012b). OWRB saw a dramatic increase in well logs reported in August 2012, and, as the drilling backlog was reduced, the amount of drilling returned to prior levels (Figure 26). This occurred after the City of Enid imposed a ban on outdoor watering from public water supplies (Enid News 2012b).

In Bethany, OK (Figure 4 and Figure 27) historical use of wells has continued despite later provision of public water (Jacobsen and Reed, 1949). Personal preference, cost of connection, and cost of monthly water are typical reasons given for continued use of private supplies. Persistence of private well use is also known in the expanding cities of Edmond (Figure 28) and Choctaw (Figure 29). Edmond reached its current extent by the end of 1976. Water mains in Edmond have largely been confined to the historic center of the city and surrounds (Figure 30), although the mains have been extended to the eastern part of the city recently. If the patterns exhibited in Bethany also exist in Edmond, however, use of private wells can be expected to persist into the future.

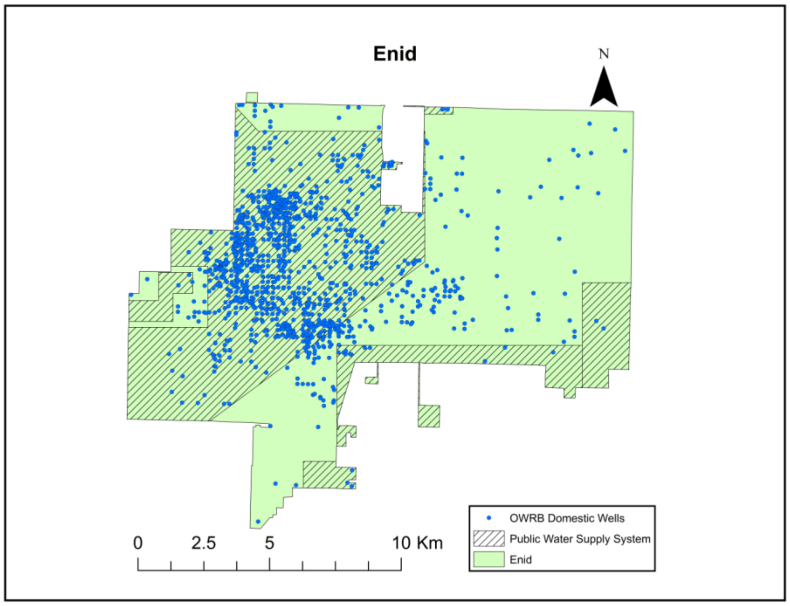
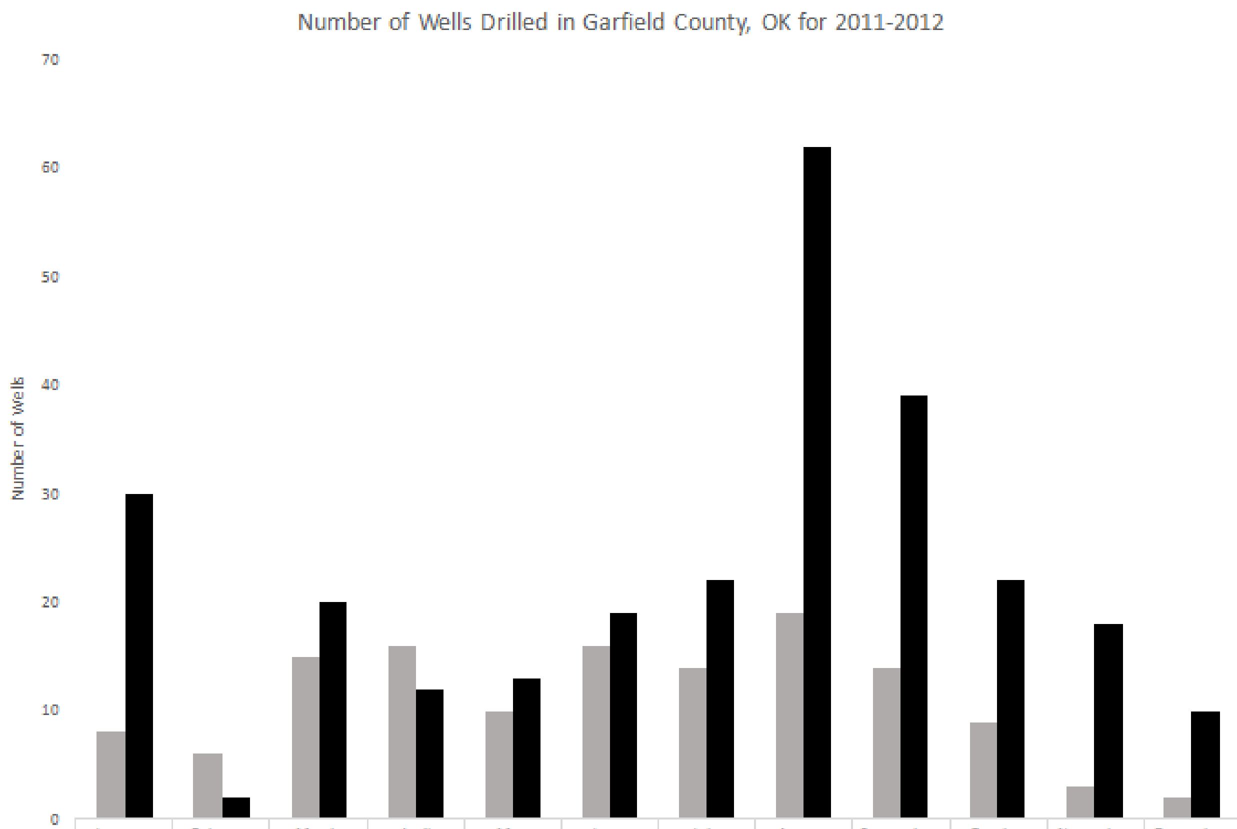


Figure 25. The City of Enid's water supply does not cover its entire territory, and contains areas with large numbers of private wells.



	January	February	March	April	May	June	July	August	September	October	November	December
2011	8	6	15	16	10	16	14	19	14	9	3	2
2012	30	2	20	12	13	19	22	62	39	22	18	10

Figure 26. Wells reported to the Oklahoma Water Resources Board in 2011 and 2012 for Garfield County (Enid). Drilling increased in August 2012 after imposition of an outdoor watering ban.

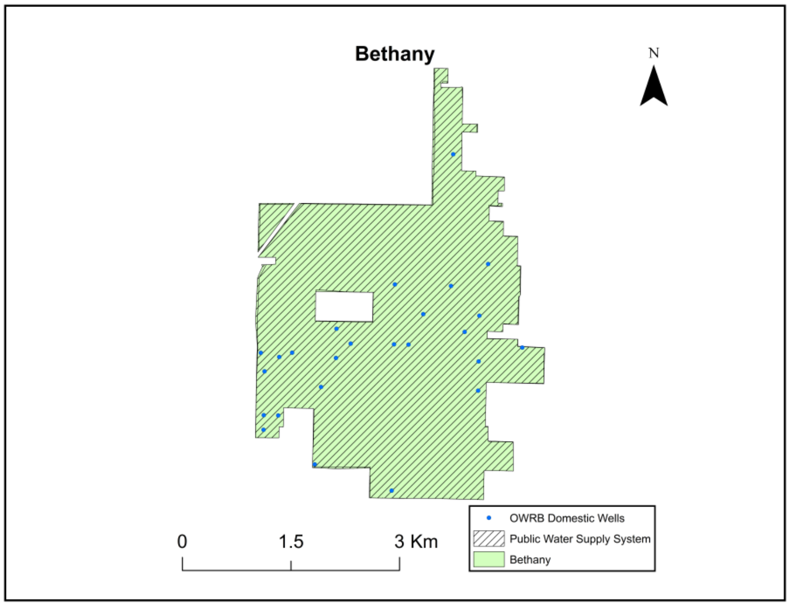


Figure 27. City of Bethany, Oklahoma, which is contained within the city limits of Oklahoma City (Figure 4).

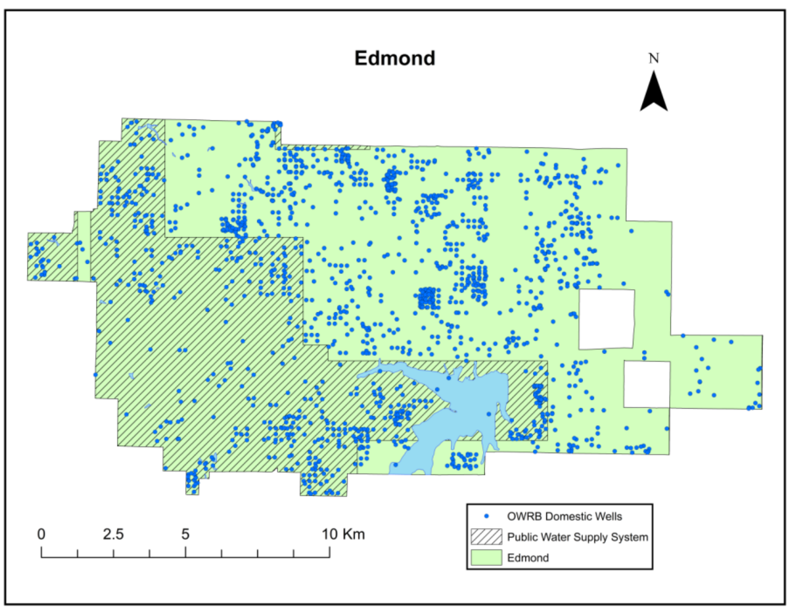


Figure 28. The City of Edmond public water supply has not extended throughout its entire territory.

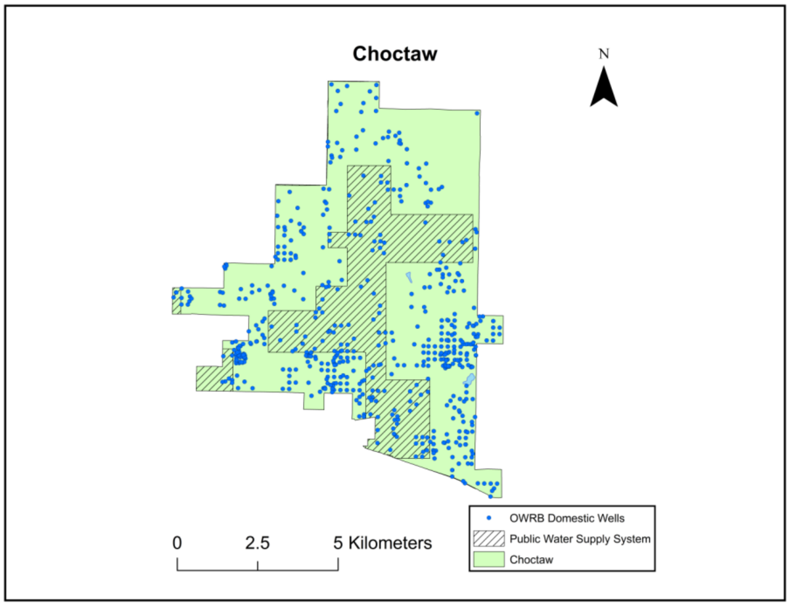


Figure 29. The City of Choctaw public water supply extends only through a portion of its territory.

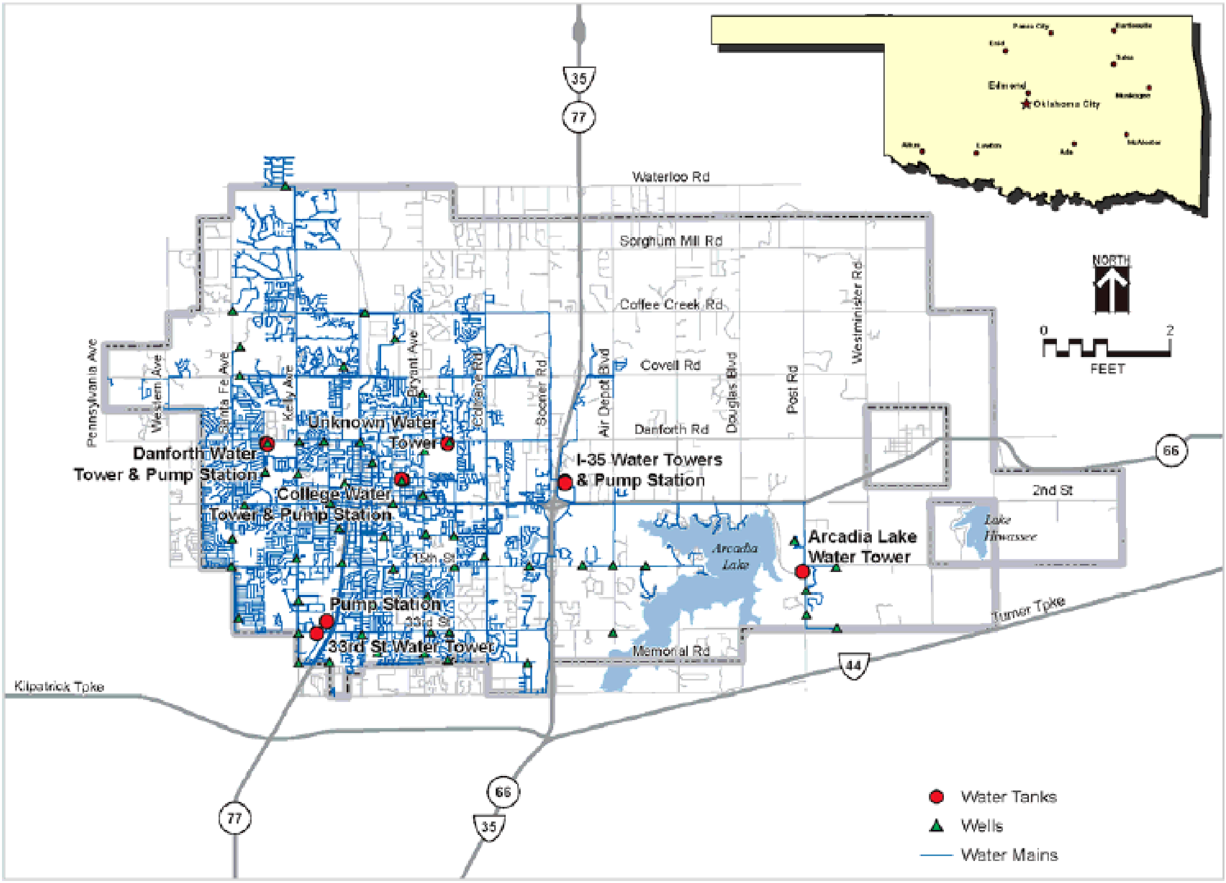


Figure 30. The location of water mains, public wells, and water tanks in Edmond, Oklahoma (2009).

Distances between Underground Storage Tanks and Private Domestic Wells

The number of tanks with wells located within the selected trial distances (15, 30, 76, 150, 230 300, and 1,610 m) was determined for both reported wells only and total estimated and reported wells for the entire state (Figure 31). Because there are appreciable numbers of estimated wells for each distance (1.2 to 2.7 times the number of reported wells, Table 8), the number of tanks estimated from the 10,000-run Monte Carlo estimates are higher than those from the known wells only. The medians from the Monte Carlo estimates are indicative of the proximity of USTs and wells and indicate that, for example, there are 9 (0.3%) USTs with wells within 15 m (50 ft), and 823 (27.1%) USTs with wells located within 300 m (1,000 ft) (Table 8). The latter distance is commonly used as a boundary by state environmental agencies, so almost 30% of tanks have a well within the distance of concern. The implications of this result are that well owners within 300 m of a UST are potentially impacted if a release occurs from the tank. Tank owners and state agency officials should have a relatively large expectation that a leaking tank has the potential to impact a residential well. Thus site investigations should include searches for private domestic wells.

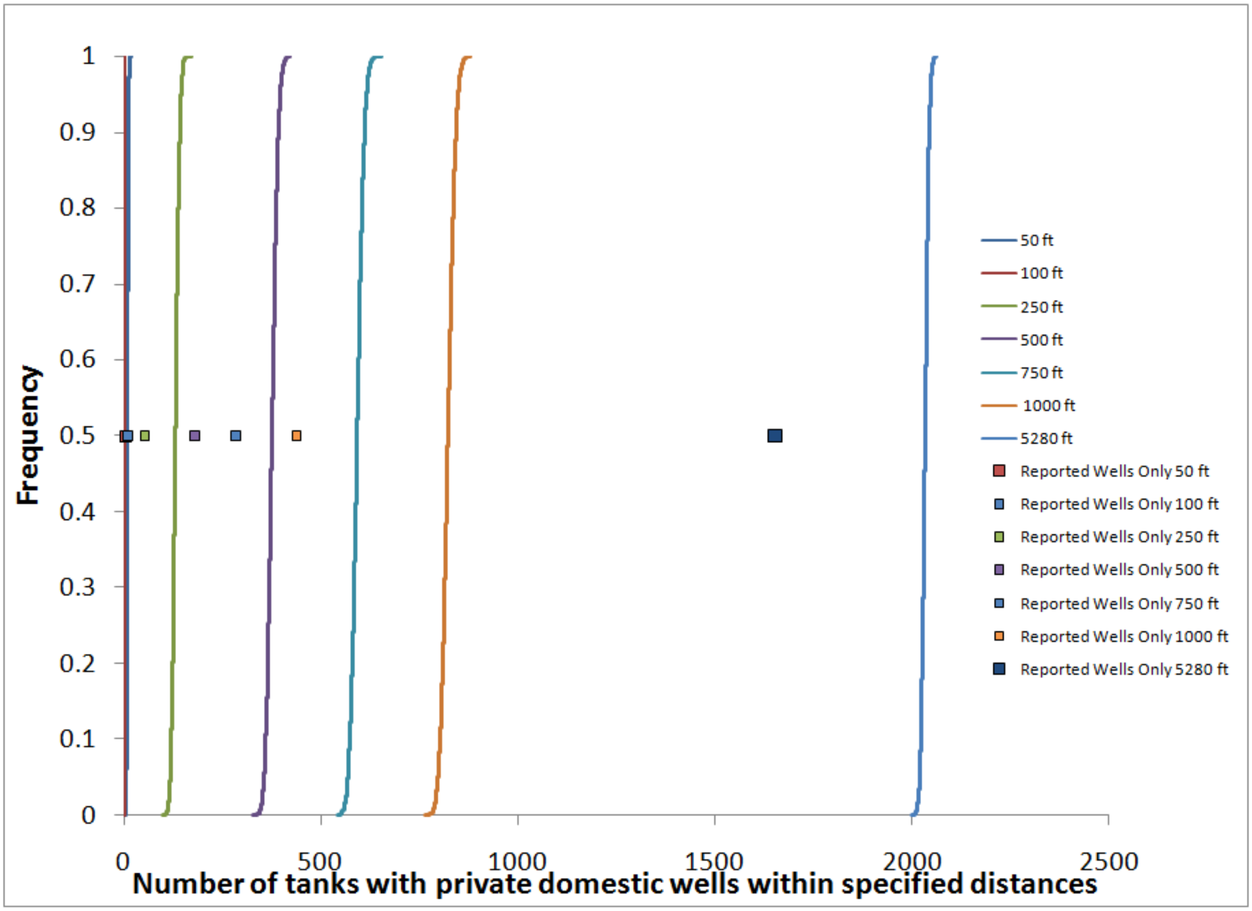


Figure 31. Frequency distribution of estimated number of USTs with PDW within specified distances from 10,000 Monte Carlo simulations of reported wells augmented with estimated locations of PDWs to match wells-added estimate of PWD density. Symbols represent numbers of USTs with only reported wells considered, plotted for comparison with median of the Monte Carlo estimate.

Table 8. Results of 10,000 Monte Carlo simulations of the distance between USTs and reported and estimated private domestic well locations. The distances were binned into categories and the counts represent the number of USTs with at least one well within the specified distance.

Distance m (ft)	Estimates of Numbers of USTs with Private Domestic Wells Within Specified Distances						Ratio [a] median to reported only result
	Reported well Locations Only	Reported and Estimated well locations 10,000 Monte Carlo Simulation Results					
		Min	25th Percentile	Median	75th Percentile	Max	
15 (50)	5	5	8	9	11	20	1.8
30 (100)	10	14	24	27	30	46	2.7
76 (250)	53	99	126	131	137	171	2.5
150 (500)	181	328	368	377	385	422	2.1
230 (750)	284	542	583	593	603	655	2.1
300 (1,000)	438	765	813	823	834	879	1.9
1,610 (5,280)	1,652	1,998	2,028	2,034	2,039	2,063	1.2

(a) Ratio of the result for the median number of USTs determined by the Monte Carlo method to the results determined from reported well locations only.

Conclusions

Inferences from the 1990 census provide a baseline for developing current estimates of areas of high density of well use and their relationship with underground storage tank sites. Oklahoma population has increased since 1990 and its reliance on private domestic wells has also increased slightly. County, census tract and census block group estimates produced consistent qualitative results for well usage, with more discrimination of spatial patterns and numerically higher estimates as the spatial size decreased. The lack of statistical significance for the county and census tract estimates suggest that the preferred analysis size is the census block group. The estimates developed by the RW and NHU methods follow established patterns evident from 1990 census results. The estimates are best viewed as indicators of areas with high or low well usage, as the data used for each method have limitations and the area associated with spatial data is no smaller than the census block group.

The reported wells method provided the most statistically significant results and is preferable for conceptual reasons: the use of reported wells allows for updating of the magnitude and spatial distribution of private domestic well use. This allows for the methodology to adapt as time progresses, as the reliance on the 1990 census inference can be lessened with time.

The well-dependent city and neighborhood estimates have the potential to be the most accurate well densities, because they include a minimum of undeveloped land, but data collection or baseline information (i.e., neighborhoods known to lack public water) needs for these methods are prohibitive on a large scale. Absent a future nationwide survey on source of water, the use of accurate and complete well completion and abandonment data from state agencies has the most potential for indirectly determining shifts in the use of wells. Over the long term, as communities expand their public water systems, however, data will be needed to assess shifts in well use that aren't reflected by well reporting only.

The estimates are useful in understanding not only the usage of private wells for water supply, but also in relation to sources of contamination that may potentially impact well users. In the case of underground storage tanks, almost 30% of tanks had at least one well within the possible extent of contamination. By identifying these tanks, environmental agencies can add this information to their protocols for prioritizing leak prevention activities, and where leaks have occurred, prioritize possibly scarce cleanup resources. Municipalities can also use this information for decisions on optimizing the locations of new gas stations to minimize the potential impact to wells.

Application of the methods developed in this paper requires the availability of widespread data, which in general are collected by state and national governments. For countries without these data, these general characteristics of areas with high reliance on wells were found:

- Expanding cities do not invest in infrastructure, either because of lack of resources or by waiting for development to support the infrastructure costs.
- Wells were used historically and later provision of public water does not induce supply change.
- Rural areas, except where
    - Infeasible due to poor quality water

    - Public water is supplied by rural water districts
    - Reliance on individual supply of surface water or cisterns

- Lawn or garden watering is taken from wells and is not the primary domestic supply.

These general characteristics are key indicators of high reliance on private domestic wells and a guide to local investigation. These methods in estimating well density can be used to assess the potential impact to private well users from potential contaminant sources, including underground storage tanks, confined animal feeding operations, industrial and hazardous waste sites, and landfills. In addition to Oklahoma, private domestic wells are an important component of overall water supply in the U.S., and understanding the geospatial relationships between these wells and potential contaminant sources is a fundamental aspect of resource management and human health protection.

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Appendix: Fluctuation of Private Domestic Well Use in Oklahoma Counties.

USGS data were used to estimate the fraction of private domestic well use in each county of Oklahoma.

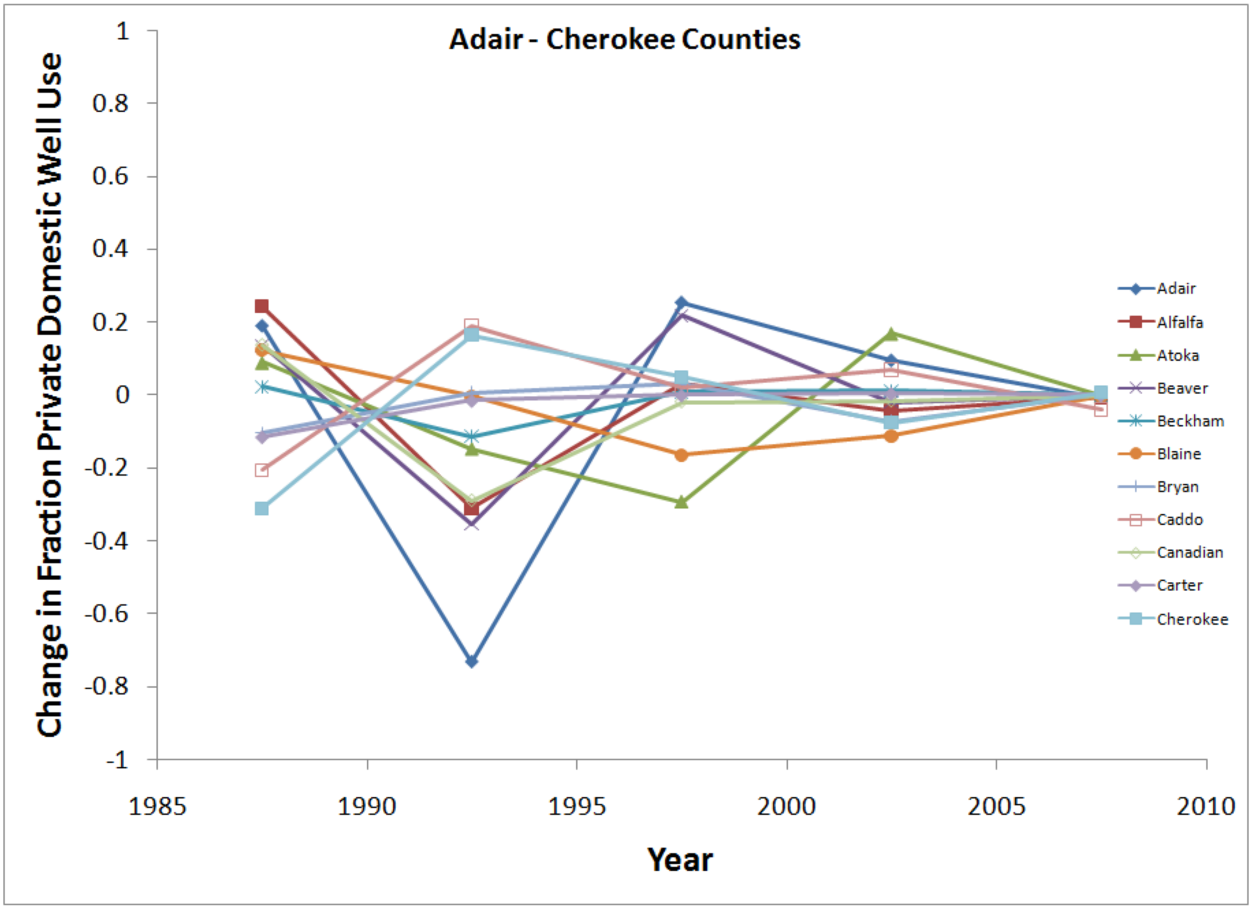

Figure 32. Changes in fraction of private domestic well use from USGS water supply data (1985-2010) for Adair to Cherokee counties.

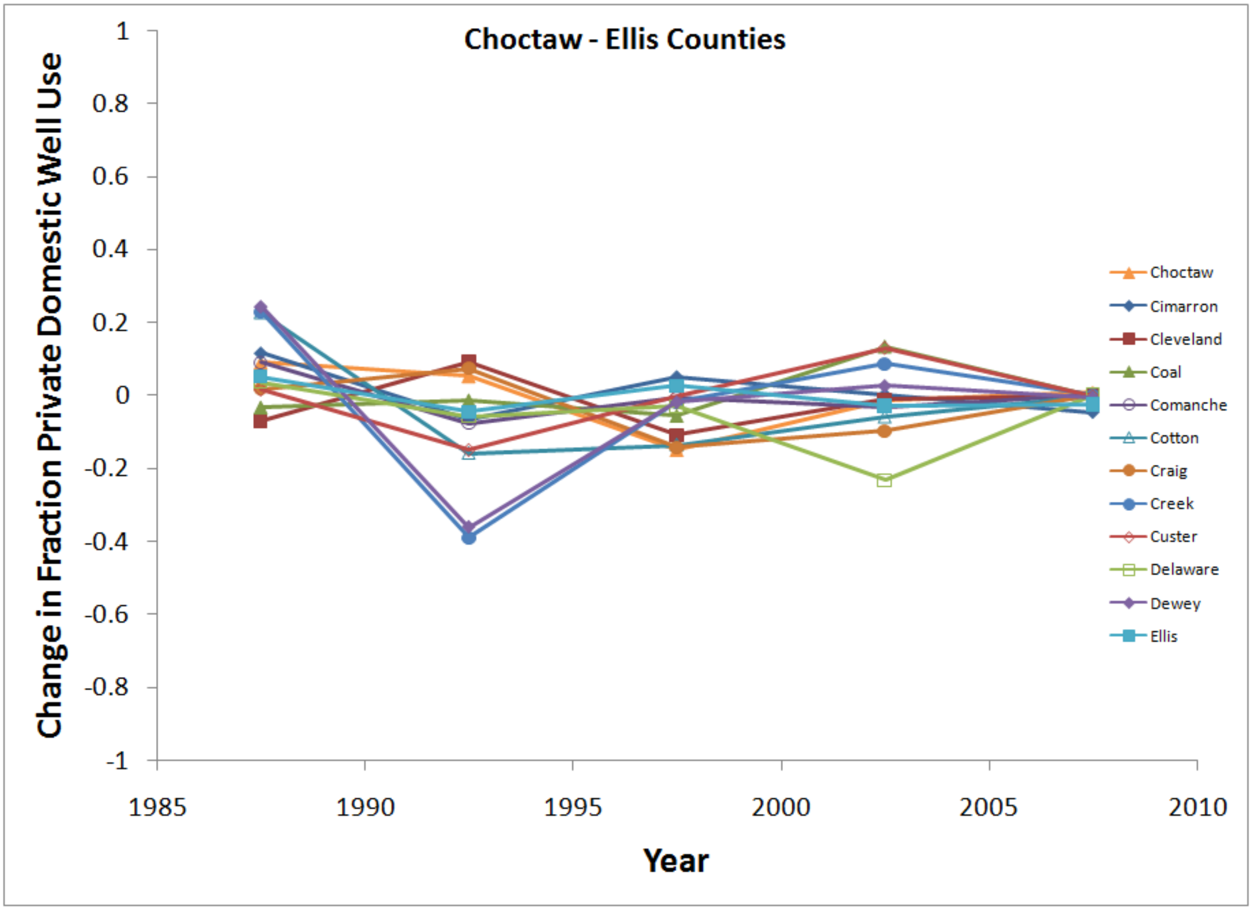

Figure 33. Changes in fraction of private domestic well use from USGS water supply data (1985-2010) for Choctaw to Ellis counties.

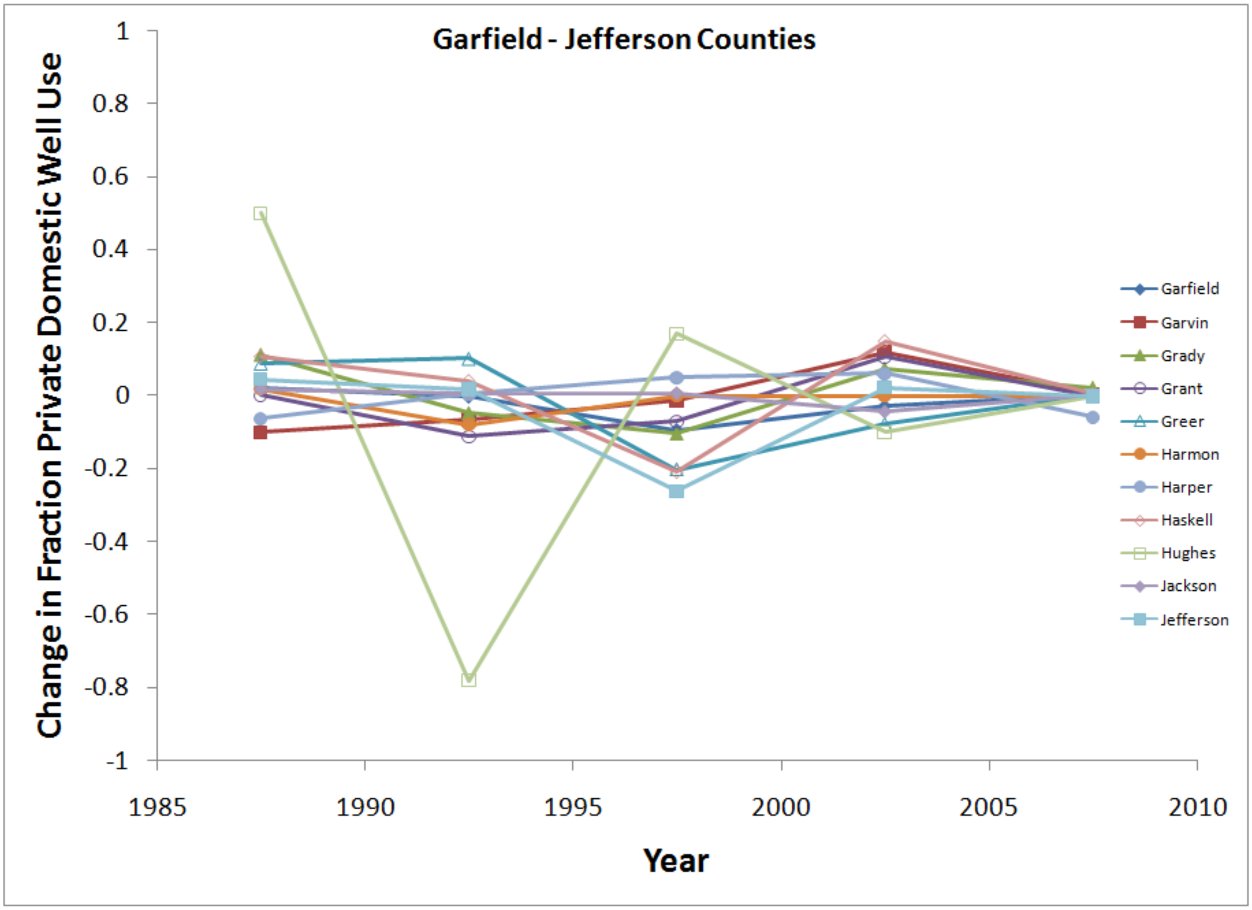

Figure 34. Changes in fraction of private domestic well use from USGS water supply data (1985-2010) for Garfield to Jefferson counties.

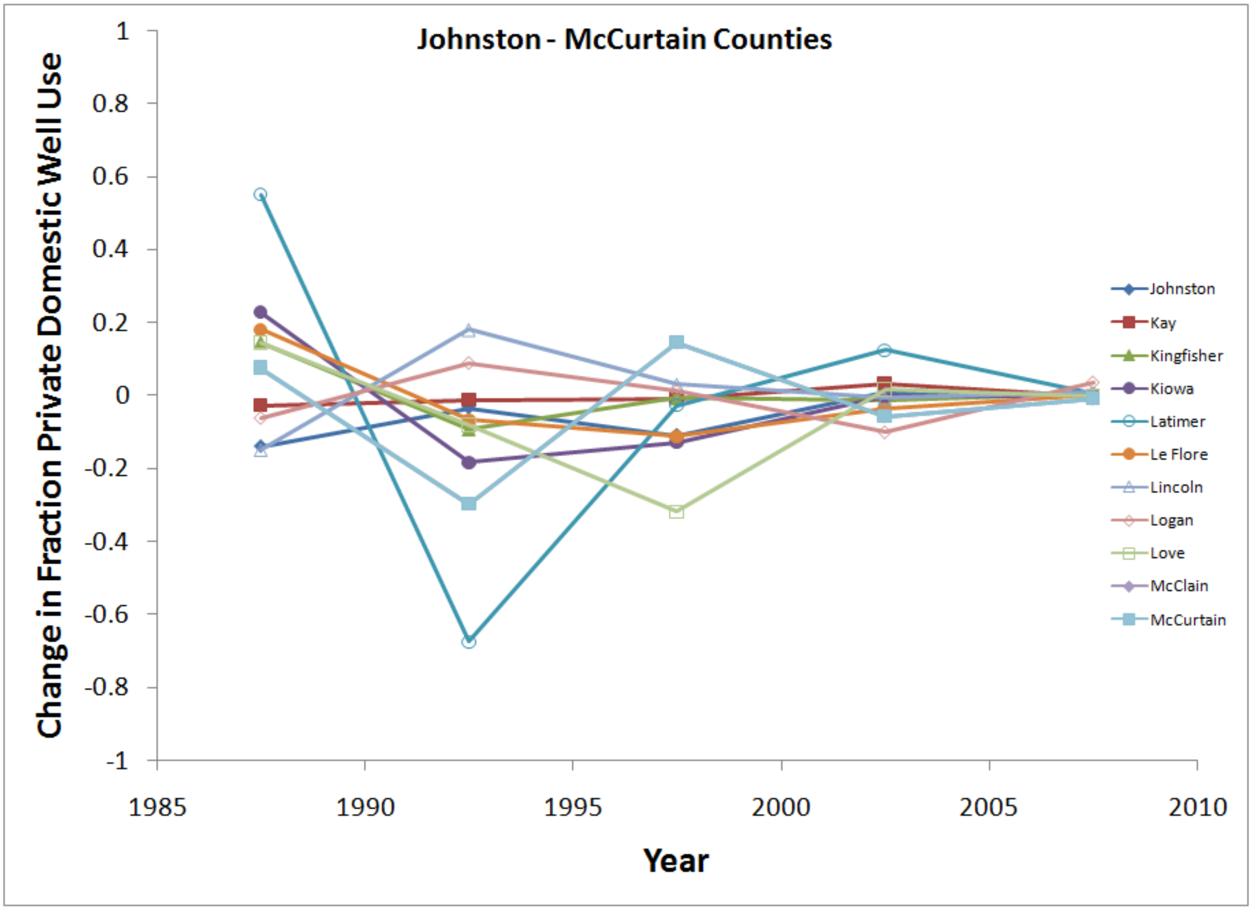

Figure 35. Changes in fraction of private domestic well use from USGS water supply data (1985-2010) for Johnston to McCurtain counties.

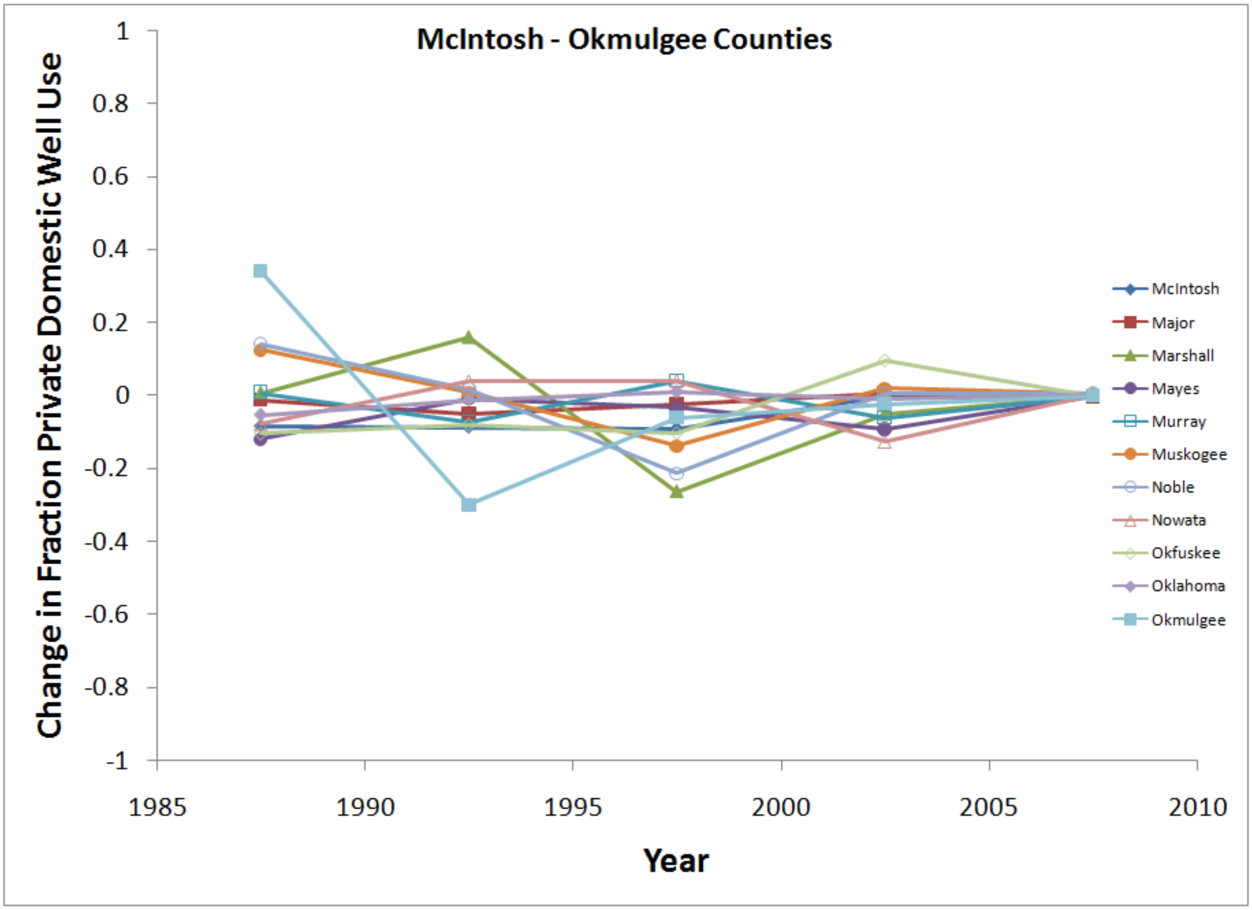

Figure 36. Changes in fraction of private domestic well use from USGS water supply data (1985-2010) for McIntosh to Okmulgee counties.

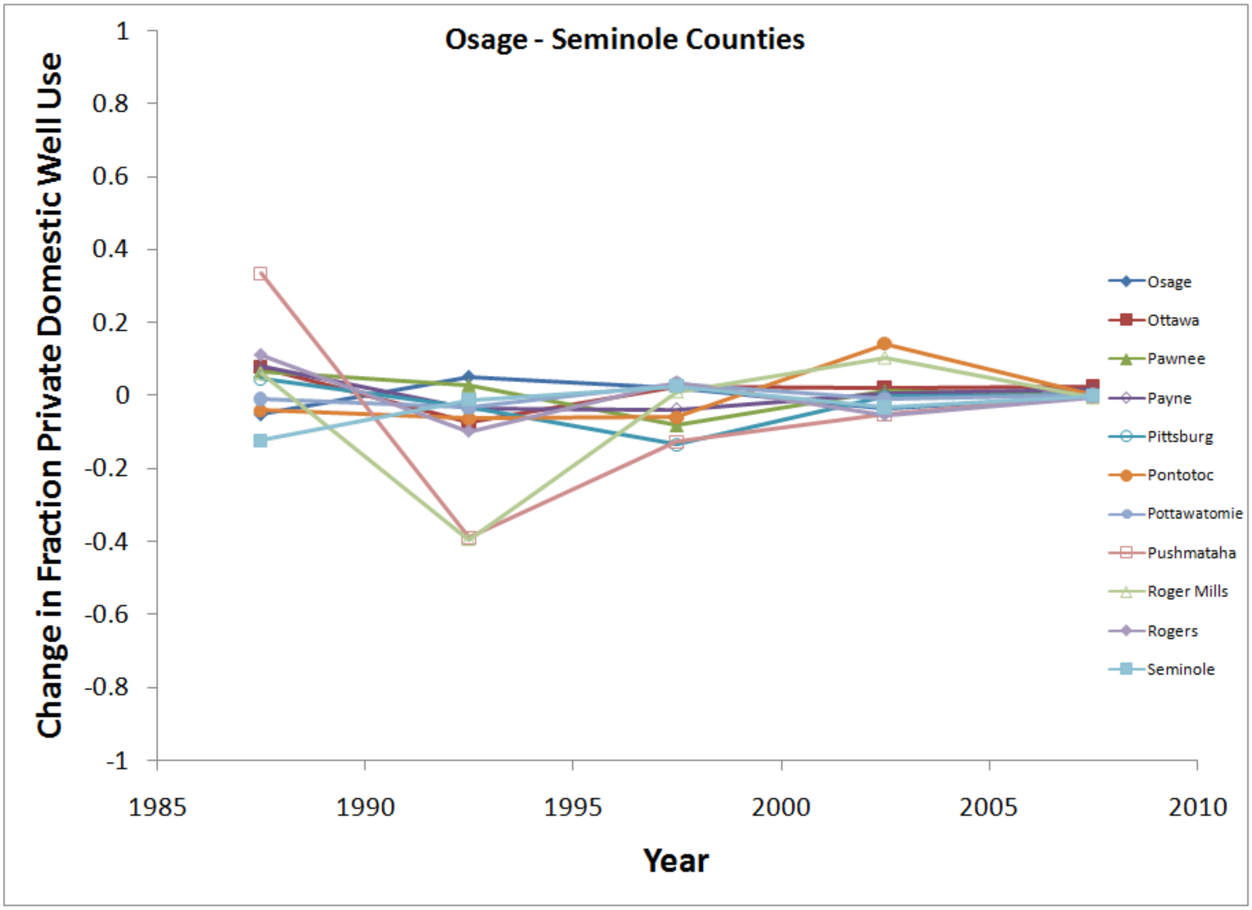

Figure 37. Changes in fraction of private domestic well use from USGS water supply data (1985-2010) for Osage to Seminole counties.

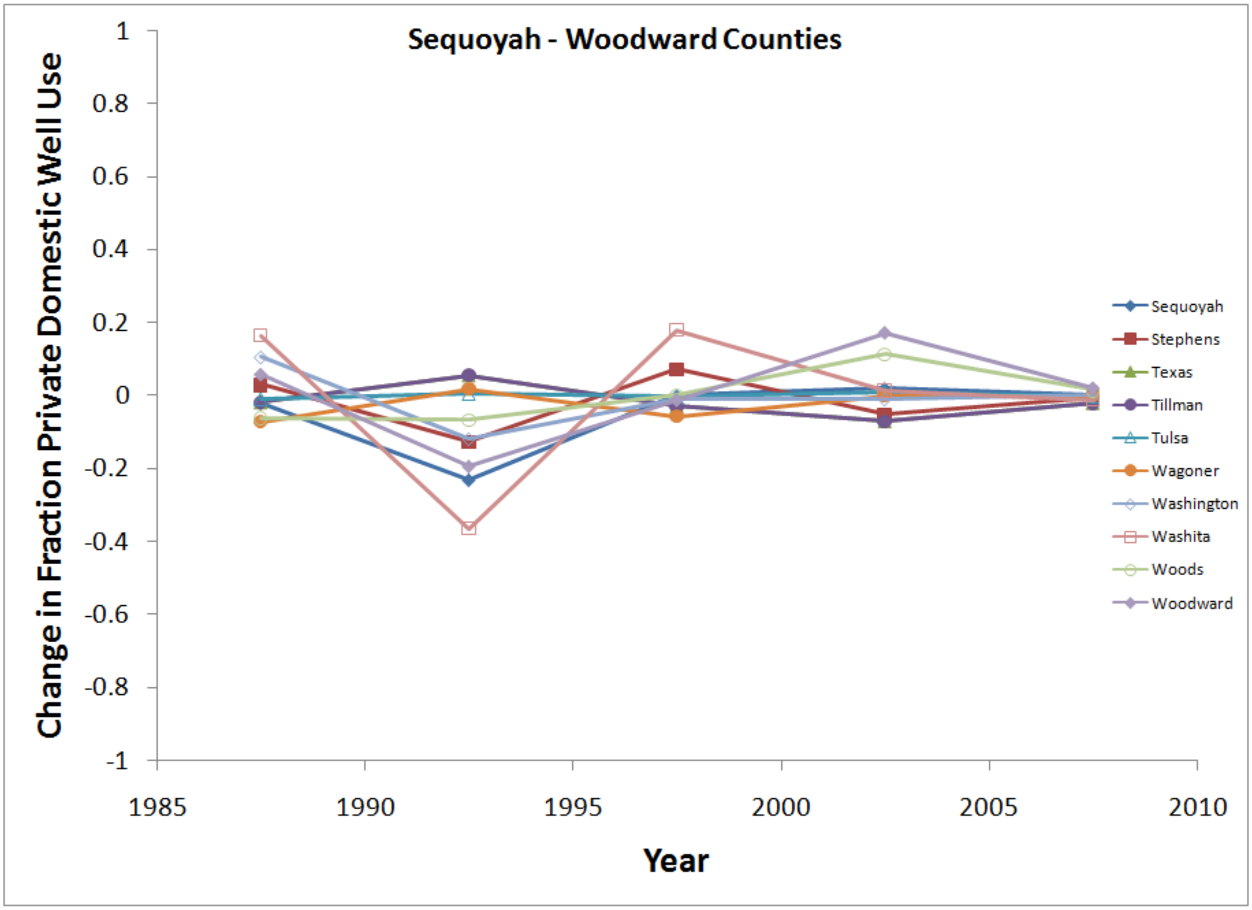

Figure 38. Changes in fraction of private domestic well use from USGS water supply data (1985-2010) for Sequoyah to Woodward counties.

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