Estimating Non-Surveyed Groundwater Use for Texas Regional and State Water Supply Planning

TWDB Contract Agreement 2500012882

Progress Report 1

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Project Goals

1. Better understand how other states, regulators, and organizations assess or project water demand for water use groups that are not monitored or reported and identify best practices that could be applied within the Texas water planning process.
2. Evaluate improved methods for estimating non-surveyed use (NSU) gallons per capita daily (GPCD) demand metrics that incorporate identified best practices and can be applied using available data and reasonable TWDB resources.
3. Test and demonstrate the improved methods by applying them to a case study area.

PROJECT PROGRESS DISCUSSION

Subtask 1. Literature Review & Data Assessment

After reviewing the existing literature, *see* **ADDENDUM A**, it is clear that no single approach fully addresses the challenges of estimating groundwater demand from NSUs.

Estimating groundwater use for non-surveyed users (NSUs) remains a complex challenge, particularly in the absence of metered data. The Gallons per Capita Daily (GPCD) method is widely used but often relies on generalized GPCD values that do not fully capture regional or seasonal differences in water use, especially for NSUs. Agencies like the USGS (e.g., Kenny & Juracek, 2012) have adopted this method, applying GPCD values derived from Census data and adjusting them using regional factors. Several western states have refined the GPCD approach to improve groundwater use estimates. Arizona's Community Water System Water Estimation Tool incorporates indoor and outdoor household use, factoring in appliance usage and landscape irrigation needs. New Mexico adjusts per capita coefficients for climate and irrigation demands, while California integrates land use data and hydrologic modeling under the Sustainable Groundwater Management Act to assess domestic well withdrawals more comprehensively.

However, the use of broad, statewide averages often results in less accurate estimates that fail to capture regional variations or seasonal fluctuations. GPCD methods also frequently overlook socioeconomic and housing variations that influence water demand. Moreover, the method struggles to accurately estimate usage for self-supplied and unmetered users, and estimates are often static, failing to account for evolving land use patterns or changes in water use behaviors over time.

The Energy-Lift Method (ELM) is widely recognized in the literature as a practical approach to estimate groundwater withdrawals, particularly when direct flow measurements are unavailable. Studies such as Hurr and Litke (1989) and guidance from the Arizona Department of Water Resources outline how energy consumption data, when combined with well construction details (e.g., pump depth, screen intervals), can estimate the volume of water pumped. The method converts energy usage into water volumes using known pump efficiencies and lift heights, providing a useful proxy for groundwater withdrawals in unmetered wells. This aligns closely with the well capacity assessment outlined in our proposal. Our initial scope focused on leveraging well construction data (e.g., pump depths, screen intervals) to estimate potential withdrawal capacities.

Other methods like remote sensing and groundwater modeling offer broader regional insights but lack the resolution needed for well-level estimates. Remote sensing (e.g., GRACE satellite data) can help validate regional depletion trends, while groundwater modeling can provide more spatially refined estimates of water level decline but require significant modeling effort. However, elements from these methods, such as aquifer drawdown data and land use maps, can still help refine our estimates. Well density and land use modeling, as demonstrated by *Murray et al. (2021)*, can also help refine estimates by mapping private well locations and correlating them with land use patterns to infer groundwater demand.

We have developed a programming script that parses the TWDB Groundwater Database and Submitted Drillers Report Database for the data required to make well capacity calculations anticipated in Subtask 2. Relevant data include: well screen interval, well screen diameter, pump depth, and pump test results (where available). Importantly, this script parses Submitted Drillers Report Database data in the legacy format. We are in the process of extracting necessary aquifer attribute data (formation thickness, hydraulic conductivity, depth, etc.) from the relevant Groundwater Availability Models (GAMs) for the expected case study area. We are extracting relevant potentiometric surface data from the GAMs and evaluating available monitoring well data. We expect to discuss water level change data in the context of Subtask 2 in further detail with TWDB.

We have collected and pre-processed preliminary climatological data (precipitation, temperature, evapotranspiration, etc.) for the study area. This data is largely ready to be spatially joined with well and aquifer data in support of Subtask 2 and 3.

Status: Upon review and compilation of the available literature, identification of existing methods and best practices, and collection of key source data, we consider the **literature review** component of Subtask 1 **complete** and the **data assessment** component **partially complete**. However, in the next three-month reporting period we may supplement the literature review to address specific components of best practices and our analysis in Subtask 2. Data assessment is ongoing. We expect to consult with TWDB and study area stakeholders regarding the availability of supplemental data and the composition of a data collection survey.

Subtask 2. Methodology Development

Armed with our findings from the literature review and data assessment conducted in Subtask 1, we have begun a preliminary evaluation of methods for assessing GPCD use estimates for NSUs. We expect to confer with TWDB on our findings prior to developing any one method in great detail.

Since we lack the critical energy consumption data needed for a full ELM application, we can adapt the method by implementing a limited ELM that focuses on estimating well capacity rather than actual water use. This approach uses standard pump efficiency assumptions and regional pumping schedules to estimate theoretical maximum withdrawals based on well infrastructure. While this introduces uncertainty since actual pump runtimes and energy usage remain unknown, it still provides valuable insights into the potential groundwater extraction capacity of non-surveyed wells.

Status: Subtask 2 has been initiated and is expected to continue in the next three-month reporting period.

Subtask 3. Case Study Evaluation

Initial consultation with TWDB suggests that Regional Water Planning Group J should be prioritized for the case study evaluation.

Status: This subtask is dependent on the completion of Subtask 2 and has therefore not yet commenced.

Project Challenges and Opportunities

As previously noted to TWDB, this project anticipated BEG personnel that ultimately were not available when expected. This resulted in a delayed start for much of this project work until the conclusion of the 2024-2025 holiday season. These issues have been resolved by reallocating existing personnel and the onboarding of Mary Eminue. The project is now proceeding apace and we expect no delays in final project completion.

ADDENDUM A

Annotated Bibliography of Literature Review

Kroepsch, A. C. (2024). Monitored but not metered: How groundwater pumping has evaded accounting (and accountability) in the Western United States. *Water Alternatives, 17*(2), 348–368. https://www.water-alternatives.org/index.php/alldoc/articles/vol17/v17issue2/745-a17-2-3/file

This study examines the lack of metering for groundwater pumping in the western United States, analyzing the systemic and historical reasons behind this challenge. The paper explores alternative methods for estimating groundwater use when metering is absent and discusses the implications for water governance and resource management.

Key Facts:

- Uses monitoring well data to assess regional groundwater trends.
- Employs remote sensing technologies (GRACE satellite data) to detect changes in groundwater storage.
- Applies proxy measurements, such as well permits and electricity consumption, to infer groundwater use patterns.

Zipper, S., Kastens, J., Foster, T., Wilson, B. B., Melton, F., Grinstead, A., Deines, J. M., Butler, J. J., & Marston, L. T. (2024). Estimating irrigation water use from remotely sensed evapotranspiration data: Accuracy and uncertainties at field, water right, and regional scales. *Agricultural Water Management, 303*, 109036. https://doi.org/10.1016/j.agwat.2024.109036

This study evaluates the effectiveness of using remotely sensed ET data, combined with other datasets, to estimate irrigation water withdrawals and applications across various scales in an intensively irrigated region of the United States. The research aims to address the challenge of unmonitored and unreported irrigation water use by providing a methodology to accurately quantify when, where, and how much water is used for irrigation purposes.

Key Facts

- Data Integration: The study integrates satellite-derived ET data with ground-based observations and water rights information to estimate irrigation water use. This approach allows for the assessment of water use at multiple scales, from individual fields to entire regions.
- Accuracy Assessment: The researchers conducted a comprehensive analysis of the accuracy and uncertainties associated with the ET-based estimates. By comparing the remotely sensed data with actual water withdrawal records, they were able to identify the strengths and limitations of the methodology across different spatial scales.

Jones, C.J.R., and Goldstein, K.M.F., 2023, Groundwater-withdrawal and well-construction data in the Upper Colorado River Basin from Arizona, Colorado, New Mexico, Utah, and Wyoming state databases, 1980–2022: *U.S. Geological Survey data release*. https://doi.org/10.5066/P9K8QV8H.

This USGS data release compiles groundwater withdrawal volumes and well construction details from the Upper Colorado River Basin across five states between 1980 and 2022. Developed to support GSFLOW modeling, the dataset integrates groundwater withdrawal volumes, well depths, and construction specifics to assist in understanding groundwater-surface water interactions.

Key Facts:

- Combines groundwater withdrawal records and well construction details from state databases and scanned driller's logs which includes data on well depths, perforated casing intervals, and geographic locations.
- Covers groundwater data spanning 42 years (1980–2022) across 142,000 square miles in five states (AZ, CO, NM, UT, WY).
- Provides recorded groundwater withdrawal volumes, including both metered and estimated data from various sources. This data is able to capture seasonal and annual withdrawal patterns to support hydrologic modeling.

Maupin, M. A., Caldwell, R. R., & Qi, S. L. (2014). ***Methods for Estimating Locations of Housing Units Served by Private Domestic Wells in the United States Applied to 2010****. (U.S. Geological Survey Scientific Investigations Report 2014–5109). U.S. Geological Survey.*
https://doi.org/10.3133/sir20145109

This study presents a national-scale methodology for estimating the spatial distribution of housing units served by private domestic wells in the United States as of 2010. Recognizing the lack of centralized data on private well locations, the authors developed a model that integrates U.S. Census housing data with state well logs to estimate well densities at the census block group level. The approach provides high-resolution maps showing the density and locations of households reliant on self-supplied domestic wells, addressing a significant data gap in groundwater resource management and planning.

Key Facts:

- The study combines 2010 U.S. Census housing data with state-level well log records to estimate the spatial distribution of housing units served by private wells.
- Uses housing unit density as a proxy to estimate private well locations in areas lacking comprehensive well log data.

Bradley, M.W., comp. (2017). Guidelines for preparation of State water-use estimates for 2015. U.S. *Geological Survey Open-File Report 2017–1029*. https://doi.org/10.3133/ofr20171029

This report provides comprehensive guidelines for compiling state-level water-use estimates for 2015 as part of the U.S. Geological Survey's National Water-Use Science Project. It outlines standardized methods for estimating water withdrawals across various categories, including self-supplied domestic use, to ensure consistency and accuracy in national water-use data.

Key Facts:

- Data Sources: Recommends utilizing U.S. Census Bureau population data and other repositories to identify households relying on self-supplied water sources.
- Per Capita Use Coefficients: Suggests applying per capita water-use coefficients, derived from studies or regional data, to estimate individual household water use.

- Estimation Formula: Proposes calculating total self-supplied domestic water withdrawals by multiplying the number of self-supplied individuals by the per capita water-use coefficient.

Chang, H., Bonnette, M. R., Stoker, P., Crow-Miller, B., & Wentz, E. (2017). Determinants of single family residential water use across scales in four western US cities. *Journal of Cleaner Production, 148, 645–654.* https://doi.org/10.1016/j.jclepro.2017.02.002

This study investigates the drivers of single-family residential water use across four western U.S. cities—Austin, Phoenix, Portland, and Salt Lake City—to understand how socioeconomic, physical, and environmental factors influence water consumption patterns. Using data at Census Block Group (CBG) and Census Tract (CT) levels, the study explores spatial variations in water use and highlights how factors like building age, property value, impervious surfaces, and climate contribute to residential water demand.

Key Facts:

- Uses buildings age as a water use indicator. Older homes, particularly in downtown areas, consistently use less water than newer suburban homes. Hence, building age can serve as a proxy for estimating water use in regions lacking direct usage data.
- Tax-assessed property value is a strong predictor of water use; higher-value homes tend to consume more water, especially for outdoor irrigation.
- Areas with greater impervious surfaces (e.g., rooftops, driveways) show higher water consumption, particularly for outdoor uses.

Dieter, C.A., & Maupin, M.A. (2017). Public Supply and Domestic Water Use in the United States, 2015. *U.S. Geological Survey Open-File Report 2017–1131.* **https://doi.org/10.3133/ofr20171131**

This report by the U.S. Geological Survey provides comprehensive data on public supply and domestic water use across the United States for the year 2015. It offers insights into total population served by public water systems, the volume of water withdrawals for public supply, and self-supplied domestic water use. The document also compares 2015 data with previous years, highlighting trends and changes in water use patterns.

Key Facts:

- The report uses U.S. Census Bureau data to determine the total population and allocates individuals to either public supply or self-supplied domestic categories.
- The national average for domestic deliveries from public suppliers was 83 gallons per capita per day (GPCD). Self-supplied domestic per capita use averaged 77 GPCD.
- The self-supplied domestic population is estimated by subtracting the population served by public supply systems from the total population.
- Self-supplied domestic withdrawals are calculated by multiplying the estimated self-supplied population by a per capita water-use coefficient which are derived from historical data, local studies, and regional water use characteristics.

- The study emphasizes the use of region-specific per capita water-use coefficients to account for variations in climate, household size, water-use habits, and system efficiencies.

Kenny, J. F., & Juracek, K. E. (2012). Description of 2005–10 domestic water use for selected U.S. cities and guidance for estimating domestic water use. *U.S. Geological Survey Scientific Investigations Report 2012-5163.* https://doi.org/10.3133/sir20125163

This study analyzes domestic water use in selected U.S. cities from 2005 to 2010 and provides guidance for estimating domestic water consumption. It examines per capita water use, identifies key factors influencing water demand, and offers methodologies for estimating unmetered domestic withdrawals.

Key Facts:

- Each USGS Water Science Center selects coefficients for self-supplied domestic use based on unpublished documentation from the 5-year NWUIP reports.
- About 65% of states, including Mississippi, Montana, and Texas**,** use standard statewide coefficients derived from previous studies, ranging from 50 to 165 GPCD**,** with a median of 76 GPCD**.**
- 35% of states, including California, Kansas, and Wisconsin, estimate self-supplied withdrawals using metered public supply data, leading to higher reported GPCD values (52 to 206 GPCD, median 98 GPCD).
- States that advantage of using statewide coefficients is simplicity, as self-supplied populations are a small portion of the total and lack direct measurement.
- Per capita water use calculation is based on recorded municipal supply and population data. Where data is missing, per capita averages for total public supply use and domestic deliveries help estimate unreported values.
- Per capita coefficients are more effective for smaller systems where population and source data are well-defined.

Bracken, N. (2010). Exempt well issues in the West. *Lewis and Clark Law School's Environmental Law Online, 47.* GAL.BRACKEN-WSWC.DOC

This report examines the challenges and policy considerations surrounding exempt wells in western U.S. states, including their impact on water resources, regulatory frameworks, and potential methods for estimating groundwater use in unmetered wells. It highlights concerns about the cumulative effect of exempt wells on regional water supplies and offers recommendations for improved estimation and management techniques. Bracken argues that while exempt wells individually may have limited impact, their growing numbers necessitate better estimation approaches to ensure sustainable water management.

Key Facts:

- Statistical Estimation Models: States can use per capita coefficients based on household size, water-use behavior, and regional trends to estimate groundwater withdrawals from exempt wells where metering is not feasible.

- Remote Sensing and GIS Mapping: Integrating well log data with spatial analysis models and land-use mapping can help identify well distribution and infer usage patterns.
- Hydrologic and Water Budget Modeling: Using hydrologic models to estimate withdrawals as a function of land use, climate, and aquifer characteristics can improve accuracy in regions with high exempt well use.

Lovelace, J. K. (2009). Method for estimating water withdrawals for livestock in the United States, 2005. *U.S. Geological Survey Scientific Investigations Report 2009-5041.* https://doi.org/10.3133/sir20095041

This report outlines a systematic approach to estimating water withdrawals for livestock across the United States in 2005. The methodology involves applying water-use coefficients (standardized estimates of daily water consumption per animal) to livestock population data at the county level. The primary data sources include the National Agricultural Statistics Service for livestock numbers and U.S. Geological Survey publications for water-use coefficients.

Key Facts:

- Uses census and agricultural records to determine livestock population data.
- Applies species-specific daily water consumption rates to estimate total demand.
- Adjusts for climate and management practices, incorporating seasonal variations.

Horn, M. A., Moore, R. B., Hayes, L., & Flanagan, S. M. (2008*). *Methods for Estimating Withdrawal and Return Flow by Census Block for 2005 and 2020 for New Hampshire. *U.S. Geological Survey Scientific Investigations Report 2007–5157*. https://doi.org/10.3133/sir20075157

This report presents methodologies developed by the U.S. Geological Survey to estimate water withdrawals and return flows at the census block level in New Hampshire for the years 2005 and 2020. The study aims to provide detailed spatial water-use data to support resource management and planning efforts. The methodologies focus on various water-use categories, including domestic, commercial, industrial, and agricultural sectors.

Key Facts:

- The study developed the New Hampshire Water Demand database to store and integrate state data central to the project. A lookup table was created to link state databases, identifying water users common to multiple databases. This facilitated the identification of withdrawal and return-flow locations for both registered and unregistered users.
- GIS data from the state were combined with U.S. Census Bureau spatial data to locate and quantify withdrawals and return flows for domestic users in each census block. This spatial analysis enabled precise allocation of water use data at a granular level.
- They applied state-developed population projections which allowed for forecasting water use for the year 2020.

Shaffer, K. H., & Runkle, D. L. (2007). Consumptive Water-Use Coefficients for the Great Lakes Basin and Climatically Similar Areas. *U.S. Geological Survey Scientific Investigations Report 2007-5197.* https://pubs.usgs.gov/sir/2007/5197/pdf/SIR2007-5197_body_pt1.pdf

This report compiles and analyzes consumptive-use coefficients for various water-use sectors within the Great Lakes Basin and climatically similar areas**.** The coefficients represent the proportion of withdrawn water that is consumed and not returned to the source due to evaporation, incorporation into products, or human/livestock consumption
Key Facts:

- **Gathers existing coefficients from published sources, providing a broad reference base.Uses reported withdrawal and consumption data to calculate consumptive-use coefficientsDerives coefficients** from withdrawal and return flow data.
- Presents statistical distributions (minimum, 25th percentile, median, 75th percentile, and maximum) for consumptive-use coefficients across various sectors including domestic, industrial, irrigation, livestock, thermoelectric power, commercial, and mining.

National Academies of Sciences, Engineering, and Medicine. (2002). Estimating water use in the United States: A new paradigm for the national water-use information program. *The National Academies Press.* https://doi.org/10.17226/10484
This report presents a new framework for improving the National Water-Use Information Program (NWUIP) in the United States. It identifies challenges in estimating national water use, focusing on the need for consistent methodologies, enhanced data collection, and improved integration of new technologies. The study highlights the difficulty in measuring consumptive water use directly and explores indirect estimation techniques, particularly for self-supplied domestic and irrigation water use.

Key Facts:

- Residual estimation approach calculates consumptive use as withdrawals minus return flow, accounting for losses such as leakage, evaporation, and public use.
- Per capita coefficients applied to demographic data to estimate self-supplied domestic water withdrawals.
- Remote sensing and water budget methods integrate satellite data (e.g., FLUXNET, Landsat) with evapotranspiration models.
- Coefficient-based models estimate demand using predefined rates per industry, household, or agricultural category.
- Statistical sampling frameworks proposed to improve confidence in water use estimates where direct data collection is impractical.

Walton, W. C. (1962). Selected Analytical Methods for Well and Aquifer Evaluation. *Illinois State Water Survey Bulletin 49.* http://hdl.handle.net/2142/94577

This report provides a comprehensive guide to evaluating wells and aquifers, focusing on the hydraulic characterization of groundwater systems. It outlines analytical methods for determining key aquifer properties such as transmissivity, storativity, and permeability, and offers techniques for assessing well performance and efficiency.

Key Facts:

- The report details procedures for conducting pumping tests and slug tests to determine aquifer properties.
- Transmissivity and storativity values obtained from these tests can be used to estimate maximum potential withdrawal rates for wells. By understanding aquifer response to pumping, it is possible to refine estimates of sustainable well yields.
- Methods for analyzing specific capacity and identifying issues like well losses are provided. These evaluations help in determining the efficiency and long-term viability of wells, which is crucial for accurate withdrawal estimations.

California

San Joaquin County Groundwater Sustainability Agencies. (2023). Eastern San Joaquin Groundwater Subbasin Water Year 2023 Annual Report*.* wy23_ar_7mar24_final.pdf

This report provides an annual assessment of groundwater conditions, extractions, recharge, and sustainability efforts in the Eastern San Joaquin Groundwater Subbasin under California's Sustainable Groundwater Management Act (SGMA). It evaluates groundwater level trends, water quality, subsidence, and groundwater use across different sectors, including municipal, agricultural, and domestic self-supplied wells. The report also details groundwater modeling efforts, monitoring network improvements, and the implementation of projects aimed at increasing water supply reliability.

Key Facts:

- Groundwater Model (ESJWRM): Estimates domestic well withdrawals using population density, land use classifications, and hydrologic conditions.
- Per Capita Water Use Approach: Applies GPCD (gallons per capita per day) values to census-based well-dependent populations to estimate withdrawals.
- Groundwater Budgeting: Uses a water balance approach that subtracts metered public supply withdrawals from total estimated groundwater use to infer self-supplied well demand.
- Public Water System Data Comparison: Benchmarks self-supplied domestic use estimates against metered public water systems for accuracy.
- Remote Sensing Pilot: Tests satellite-based evapotranspiration models to refine estimates of groundwater withdrawals.
- Climate Adjustments: Incorporates seasonal and drought-based variations to refine groundwater use estimates, recognizing increased pumping demand during dry years.

California Department of Water Resources. (2022). Options for Measuring Groundwater Extraction Volumes*.* https://www.waterboards.ca.gov/sgma/docs/reporting/measuring_gw.pdf

This document outlines methodologies for estimating groundwater extraction using power consumption data, pump curves, and computer-based models. The report highlights how pump efficiency, well depth, and system losses impact accuracy and provides guidance on adjusting calculations for varying field conditions.

Key Facts:

- Using pump energy consumption to estimate withdrawals, applicable where no direct flow meters exist**.**
- Requires knowledge of pump efficiency and well characteristics (e.g., depth to water, system losses) for accurate volume calculations.
- Computer-based algorithms refine estimates**,** reducing errors from seasonal variations and power fluctuations**.**
- Challenges include variations in pump performance and external power influences, which require calibration for reliable use.

Thatch, L. M. (2018). Untangling Water Management and Groundwater Extraction Signals in the California Central Valley: An Integrated Hydrologic Model and Remote Sensing Synthesis Approach. (Master's thesis, Colorado School of Mines). https://hdl.handle.ne t/11124/172360

This study combines the ParFlow-CLM integrated hydrologic model with remote sensing data from NASA's GRACE satellite to evaluate groundwater extraction and storage changes in California's Central Valley. The research identifies how water management activities, particularly during drought periods, influence groundwater depletion.

Key Facts:

- ParFlow-CLM Model: Simulates groundwater extraction and irrigation scenarios to estimate water storage changes.
- GRACE Satellite Data: Provides estimates of total water storage anomalies (TWSA) to validate model outputs.
- Simulation Comparisons: Evaluates multiple groundwater extraction and irrigation scenarios to identify dominant factors influencing water storage fluctuations.

Burt, C. M. (2017). Using Electricity Consumption to Estimate Water Volumes Pumped from Wells. *Irrigation Training and Research Center (ITRC), California Polytechnic State University.* https://digitalcommons.calpoly.edu/bae_fac/239/

This report critically examines the use of electricity consumption data to estimate groundwater withdrawals from wells. It highlights how variations in pump efficiency, groundwater levels, and operational conditions can distort estimates. Burt emphasizes the limitations of the Energy-Lift Method, showing that relying solely on energy consumption as a proxy for water volume can lead to inaccuracies, particularly when efficiency losses or system changes aren't accounted for.

Key Facts:

- Pump efficiency fluctuates due to wear, changing groundwater levels, and variable flow rates, leading to inaccuracies in energy-based estimations.
- The Energy Lift Method (ELM) assumes a constant relationship between energy use and water pumped, which is often invalid due to fluctuating operational conditions and pump performance.
- Includes visual analyses illustrating how energy consumption data can misrepresent actual pumped volumes, particularly when system inefficiencies are not factored in.

Water in the West, Stanford University. (2016). **Projecting forward: A framework for groundwater model development under the Sustainable Groundwater Management Act.** *Water in the West Report Series.* https://waterinthewest.stanford.edu/sgma-report-series

This report explores the development of groundwater models under SGMA, focusing on strategies to improve estimates of unmetered groundwater use. It presents best practices for using modeling tools and indirect estimation techniques in the absence of direct pumping data.

Key Facts:

- Promotes groundwater flow models incorporating domestic well withdrawals as a key parameter for regional water budgeting.
- Suggests using census population data and well density analysis to estimate self-supplied domestic groundwater demand.
- Recommends machine learning techniques and remote sensing data to validate domestic groundwater withdrawal estimates.
- Highlights the need for long-term groundwater monitoring networks to improve non-surveyed water use estimates over time.

U.S. Geological Survey. (2009). Groundwater Availability of the Central Valley Aquifer, California. *Reston, VA: U.S. Department of the Interior.* https://doi.org/10.3133/pp1766

This study evaluates groundwater availability in California's Central Valley, focusing on agricultural and urban water use, including unmetered wells. The Central Valley Hydrologic Model integrates land use, water management, and hydrologic data to simulate groundwater flow and pumpage.

Key Facts:

- Farm Process (FMP): Calculates agricultural pumpage as the residual irrigation demand, considering surface-water supply, precipitation, and irrigation efficiency.
- Multi-Node Well (MNW) Package: Simulates vertical flow through wells penetrating multiple aquifer layers, allocating pumpage based on perforated well intervals.
- Estimation for Unmetered Wells: Uses residual irrigation demand, mass balances, and land use integration to estimate groundwater pumpage.

Martindill, N., et al. (2021). Estimating Agricultural Groundwater Withdrawals with Energy Data. *Journal of Water Resources Planning and Management, 147(5), 04021018.*

https://doi.org/10.1061/(ASCE)WR.1943-5452.0001348

This study explores the Efficiency Lift Method (ELM), which estimates groundwater extraction by analyzing electricity consumption data from pumping systems. The method leverages the relationship between energy use and water pumped to provide estimates of groundwater withdrawals.

Key Facts:

- Utilizes detailed electricity usage data and pump operating conditions to calculate groundwater extraction.
- Converts energy consumption into water volume estimates, providing a practical approach for areas lacking direct flow measurements.

Colorado

Maupin, M. A., Ivahnenko, T., & Bruce, B. (2018). Estimates of water use and trends in the Colorado River Basin, Southwestern United States, 1985–2010. *U.S. Geological Survey Scientific Investigations Report 2018-5049.* https://doi.org/10.3133/sir20185049

This report examines water-use trends across the Colorado River Basin from 1985 to 2010, evaluating total groundwater and surface water withdrawals for multiple sectors, including domestic, agricultural, and industrial uses. The study compiles historical water-use data and applies hydrologic models to assess long-term trends and changes in water allocation.

Key Facts:

- Uses per capita water-use coefficients and census-based data to estimate self-supplied domestic groundwater withdrawals.
- Analyzes trends in self-supplied groundwater use by integrating demographic shifts and water-use patterns.
- Employs hydrologic models to assess groundwater depletion and changes in recharge over time.

Fredericks, J. W., Labadie, J. W., & Altenhofen, J. M. (1998). Decision support system for conjunctive stream-aquifer management. *Journal of Water Resources Planning and Management*, 124(2), 69–78. https://doi.org/10.1061/(ASCE)0733-9496(1998)124:2(69)

This report presents a decision support system (DSS) designed for the conjunctive management of surface water and groundwater resources. The system integrates streamflow models with aquifer simulations to optimize water allocation, focusing on sustainable water use while balancing ecological and legal constraints. The study emphasizes the importance of modeling stream-aquifer interactions for more effective water resource management.

Key Facts

- MODSIM incorporates the capability to model stream-aquifer interactions, allowing for the assessment of conjunctive use strategies that optimize the combined use of surface and groundwater resources.
- Users can input parameters such as maximum well field pumping rates and pumping priorities to simulate the integration of groundwater withdrawals into the overall water supply system.

Hurr, R. T., & Litke, D. W. (1989). Estimating pumping time and ground-water withdrawals using energy-consumption data. *U.S. Geological Survey Water-Resources Investigations Report 89-4107.* https://doi.org/10.3133/wri894107

This report presents an approach for estimating groundwater withdrawals from unmetered wells using energy consumption data. The study introduces the rate-time method, which relates pump energy usage to estimated withdrawal volumes, making it useful for cases where direct flow measurements are impractical.

Key Facts:
- Estimates pumping duration by dividing total energy consumed by the power demand of the pumping system.
- Introduces the Power-Consumption Coefficient (PCC), which quantifies the relationship between power demand and pumping rate.
- Enables regional groundwater withdrawal estimation by sampling PCCs across multiple sites.

Arizona

Tadych, D. E., Ford, M., Colby, B. G., & Condon, L. E. (2024). Historical patterns of well drilling and groundwater depth in Arizona considering groundwater regulation and surface water access. *Journal of the American Water Resources Association, 60*(1), 45-67. https://doi.org/10.1111/1752-1688.13234

This study examines groundwater trends in Arizona by analyzing historical well drilling patterns and groundwater depth changes. The research explores how groundwater regulation and surface water access influence water resource management. Utilizing well data from the Arizona Department of Water Resources, the study assesses groundwater depletion and identifies regions with the most significant declines. Findings indicate that while regulated areas experience more controlled groundwater use, unregulated and exempt domestic wells continue to contribute to groundwater depletion, particularly in rural and peri-urban areas.

Key Facts:
- The study applies spatial analysis of well drilling records, historical groundwater depth measurements, and trends in regional groundwater availability to infer usage patterns from exempt wells.

- Compares changes in well drilling rates before and after the introduction of groundwater management policies to estimate the extent of reliance on unregulated wells. Additionally, it evaluates shifts in groundwater depth data over time to assess the cumulative impact of self-supplied domestic withdrawals in different hydrogeologic settings, providing indirect estimates of groundwater extraction.

Majumdar, S., Smith, R., Conway, B., & Lakshmi, V. (2022). Advancing remote sensing and machine learning-driven frameworks for groundwater withdrawal estimation in Arizona: Linking land subsidence to groundwater withdrawals. *Hydrological Processes*. https://doi.org/10.1002/hyp.14757

This study employs a machine learning-driven approach to estimate groundwater withdrawals across Arizona, integrating remote sensing datasets with hydrologic indicators. The model predicts groundwater withdrawals from 2002 to 2020 at a 2 km spatial resolution, utilizing well density, land use, evapotranspiration, and precipitation data as primary inputs. The study validates its results using in situ pumping data from the Arizona Department of Water Resources (ADWR).

Key Facts:

- Data Integration**:** Uses remote sensing products like SSEBop evapotranspiration, USDA-NASS land use data, PRISM precipitation data, and crop coefficients.
- Predictor Variables: Incorporates well density and watershed water stress indices as predictors in the machine learning model.
- Validation and Application: Compares estimated groundwater withdrawals with land subsidence data from Interferometric Synthetic Aperture Radar (InSAR) to assess the relationship between groundwater extraction and land deformation.

Arizona Department of Water Resources (ADWR). (2017). Annual Report 2017. *Phoenix, AZ: ADWR*. https://www.azwater.gov/sites/default/files/2022-08/Annual_Report_2017.pdf

The ADWR's 2017 Annual Report provides a comprehensive overview of the state's water resources management activities, including groundwater monitoring, well registrations, and water budgeting efforts. The report emphasizes the importance of balancing water inputs and outputs within Arizona's aquifer systems to ensure sustainable groundwater use.

Key Facts:

- **Data Integration:** The report compiles various hydrologic datasets, including precipitation records, aquifer recharge estimates, streamflow measurements, and evapotranspiration data, to assess the overall water balance.
- **Water Budget Analysis:** ADWR employs a comprehensive water budget approach to evaluate the balance between water inputs and outputs within aquifer systems. Discrepancies between measured inflows and outflows are analyzed to identify unaccounted-for groundwater withdrawals, which may include usage from non-metered or private wells.

Arizona Department of Water Resources (ADWR). (n.d.). Community Water System Water Estimation Tool. *Arizona Department of Water Resources*. https://www.azwater.gov/sites/default/files/media/CWS%20Water%20Estimation%20Tool.xlsx

The Community Water System Water Estimation Tool is designed to estimate water use for community water systems in Arizona by calculating **indoor and outdoor household water use**. It applies per capita **gallons per day (GPCD)** rates based on common household appliance usage and landscape irrigation needs to derive total water demand. The tool is particularly useful for estimating water use in non-metered households and private well users by relying on assumed usage patterns and appliance efficiency levels.

Key Facts:

- Indoor Water Use Calculation: Uses predefined GPCD values for toilets, showers, baths, faucets, dishwashers, and clothes washers.
- Household-Based Estimation: Estimates total indoor water use by multiplying per-person GPCD by the number of residents.
- Outdoor Water Use Calculation: Incorporates landscaping measurements and irrigation type to estimate exterior water demand.

Arizona Department of Water Resources (ADWR). (n.d.). Estimating Water Use from Energy Records. *Arizona Department of Water Resources.* Microsoft Word - estimating water use final.doc

This report provides methods for estimating groundwater withdrawals using energy consumption records from well pumps. It presents multiple approaches, including calculations based on pumping time, power consumption, and discharge rates, making it useful for wells lacking direct water metering.

Key Facts:

- Pipe Flow & Discharge Method: Uses energy records + periodic discharge measurements to estimate total groundwater withdrawals.
- Hour Meter Method: Tracks pump operation time combined with known flow rates to derive annual extraction.
- Energy-Only Estimation: Converts electricity or natural gas consumption into estimated groundwater withdrawals using efficiency factors.

Smith, K. L. (2015). Groundwater: Getting to Safe Yield by 2025. *Grand Canyon Institute*. https://grandcanyoninstitute.org/wp-content/uploads/2015/06/GCI_Policy_GroundwaterGettingtoSafeYieldby2025_February2015.pdf

This report discusses the challenges of achieving safe yield in Arizona by 2025, focusing on the lack of regulation and monitoring of unmetered domestic wells**,** which continue to contribute to groundwater depletion. It highlights that current groundwater models do not fully account for exempt well withdrawals**,** making it difficult to quantify their impact on water budgets. The report calls for policy reforms to include unmetered wells in groundwater reporting requirements to improve tracking of overall groundwater withdrawals.

Key Facts:

- Author notes that existing models do not fully account for exempt wells, leading to inaccurate groundwater budgets.
- Emphasizes enhanced monitoring, regulation, and comprehensive groundwater management to reach safe yield targets.
- Urges consistent methodologies for estimating groundwater use, particularly for non-metered sources.

Anderson, M. T., Pool, D. R., & Leake, S. A. (2007). The water supply of Arizona: The geographic distribution of availability and patterns of use.
https://www.taylorfrancis.com/chapters/edit/10.4324/9781936331390-4/water-supply-arizona-mark-anderson-donald-pool-leake-stanley

This chapter examines Arizona's water supply, covering surface water, groundwater, and storage systems. It discusses the impact of population growth, groundwater depletion, and water management strategies. The study highlights legal frameworks and conservation efforts to balance water use and sustainability.

Key Facts:

- Authors discuss methods such as water budget analyses, which involve accounting for all water inputs and outputs within a system to estimate unmeasured extractions.
- Groundwater depletion is assessed using well drilling trends, water level measurements, and remote sensing to infer groundwater extraction volumes where direct measurements are unavailable.

New Mexico

Santa Fe County. (2023). La Cienega and La Cieneguilla Domestic Well Monitoring Program Report. *Santa Fe County Water Resources Department.*
https://www.santafecountynm.gov/uploads/documents/La_Cienega-La_Cieneguilla_Domestic_Well_Report_3-27-2023_Final.pdf

This report presents findings from a domestic well monitoring program in the La Cienega and La Cieneguilla communities. It assesses groundwater levels, usage patterns, and water quality, comparing trends in private wells with community water system data. The report highlights the challenges of estimating water use in self-supplied households due to the lack of metering and emphasizes the need for improved monitoring.

Key Facts:

- Groundwater Level Trends: Tracks changes in well water levels to assess long-term depletion risks.

- Private vs. Public Supply Analysis: Compares community water system data to infer domestic well usage patterns.
- Monitoring Network: Implements voluntary well measurement programs to collect water use data from self-supplied households.
- Challenges in Estimation: Acknowledges difficulties in estimating private well withdrawals due to lack of direct metering.

Rinehart, A. J., & Mamer, E. (2017). Groundwater Storage Change in New Mexico Aquifers: Pecos Slope and Southern High Plains.
https://geoinfo.nmt.edu/geoscience/research/documents/19/WRRI_TechCompReport-June2017.pdf

This comprehensive report is divided into two parts. Part 1 introduces a methodology for estimating groundwater storage changes in variably confined aquifers, which transition between confined and unconfined states. The method accounts for elastic deformation in confined zones and pore space drainage in unconfined zones, providing a nuanced approach to assess storage variations. Part 2 applies this methodology to the Southern High Plains Aquifer in New Mexico, offering empirical estimates of storage changes over time.

Key Facts:

- Utilizes water-level measurements and aquifer properties to calculate storage variations.
- Incorporates spatial variability in aquifer confinement to enhance accuracy.

Newton, B. T., Ketchum, D. G., & Phillips, F. M. (2016). High-Resolution Estimation of Groundwater Recharge for the Entire State of New Mexico. *New Mexico Water Resources Research Institute Technical Completion Report No. 372.* https://nmwrri.nmsu.edu/statewide-water-assessment/research-project-categories/reports/recharge-reports/y2-final-report-NEWTONRecharge_Technical_Completion_2016.pdf

This study introduces the Evapotranspiration and Recharge Model (ETRM), a soil water balance model developed to estimate groundwater recharge across New Mexico at a high spatial resolution (250 meters). The ETRM integrates daily precipitation data, soil characteristics, vegetation indices, and evapotranspiration rates to simulate water fluxes. Results indicate that approximately 6.1% of the state's annual precipitation contributes to groundwater recharge, with higher recharge rates observed in mountainous regions due to increased precipitation and lower evapotranspiration.

Key Facts:

- Soil Water Balance Approach: The ETRM tracks water inputs (precipitation) and outputs (evapotranspiration, runoff, deep percolation) to estimate groundwater recharge.

- Model Inputs: The ETRM utilizes PRISM daily precipitation data, STATSGO and SSURGO soil databases, MODIS-based vegetation indices, and the National Land Cover Dataset (NLCD) to inform its simulations.

New Mexico Office of the State Engineer. (2017). Guidelines for the assessment of drawdown estimates for water right application processing. *Hydrology Bureau Report 05-17.* https://www.ose.nm.gov/Library/HydrologyReports/DRAWDOWN%20ASSESSMENT%20GUIDELINES%202017.pdf

This report outlines methodologies for evaluating the impact of groundwater withdrawals on existing wells in New Mexico as part of the water rights application process. It provides guidelines for estimating drawdown effects to prevent impairment of neighboring wells and ensure sustainable water use. While primarily intended for regulatory assessments, the methodologies for drawdown estimation could be adapted to infer groundwater withdrawals in regions where well metering is not available.

Key Facts:

- Drawdown Analysis: Provides guidelines on calculating water level declines in response to pumping, offering insights into aquifer response to withdrawals.
- Aquifer Testing: Recommends using well tests to determine aquifer transmissivity and storativity, which influence groundwater availability.
- Impact Assessment: Identifies potential well interference and depletion effects from new groundwater withdrawals.

Utton Center. (2014). Water Matters! Groundwater. *Utton Transboundary Resources Center, University of New Mexico School of Law.* https://uttoncenter.unm.edu/assets/docs/publications/water-matters-2015/06_Groundwater.pdf

This publication provides an overview of groundwater development and management in New Mexico, highlighting its historical evolution, legislative milestones, and current challenges. The report emphasizes the critical role of groundwater, supplying nearly half of the state's water needs, and discusses issues such as aquifer depletion, the interconnection between surface and groundwater, and the necessity for sustainable management practices to address declining water tables.

Key Facts

- Groundwater development in New Mexico began in the late 19th century, intensifying during drought periods and post-World War II due to technological advancements and population growth.
- The 1931 Groundwater Code granted the State Engineer authority over groundwater resources, enabling the declaration and management of groundwater basins to protect senior water rights.

- Excessive groundwater withdrawal, or "mining," has led to declining water tables in several basins, necessitating conservation efforts and regulatory measures to prevent resource depletion.
- Average household water use in New Mexico is estimated to be 0.25 to 0.33 acre-feet per year. This figure is multiplied by the total number of domestic wells to approximate water use.
- Water usage patterns from metered community water systems are analyzed to infer usage rates for domestic wells with similar household characteristics.

Santa Fe County. (2015). La Cienega and La Cieneguilla Community Plan Update. *Santa Fe County*. https://www.santafecountynm.gov/media/files/2015LaCienegaandLaCieneguillaPlanUpdate.pdf

This update provides an assessment of water usage trends in the La Cienega and La Cieneguilla communities, detailing changes in groundwater reliance, well conditions, and conservation efforts. The report outlines concerns over declining water tables, increased demand from new developments, and the impact of climate variability on local aquifers. Strategies for improving water management, including conservation policies and potential infrastructure enhancements, are also discussed.

Key Facts

- Declining Groundwater Levels: Reports show a gradual decrease in aquifer levels, with growing concern over future availability.
- Increased Domestic Well Use: More households rely on private wells, increasing pressure on groundwater resources.
- Water Conservation Initiatives: Encourages low-water landscaping and improved irrigation efficiency to reduce overall demand.
- Monitoring and Policy Recommendations: Suggests improved well monitoring and potential regulatory changes to better manage groundwater use.

Longworth, J. W., Valdez, J. M., Magnuson, M. L., & Richard, K. (2013). New Mexico Water Use by Categories 2010. *New Mexico State Engineer Office, Technical Report 54.* Chapter 6

This report provides an overview of groundwater management and self-supplied domestic water use estimation in New Mexico. It highlights challenges in quantifying withdrawals due to the lack of metering, examines regional variations in water consumption, and evaluates methodologies for improving estimates. The study discusses the impact of domestic wells on surface water resources, regulatory considerations, and potential improvements for groundwater sustainability.

Key Facts:

- The study assumes that all individuals not connected to public water systems (PWS) rely entirely on self-supplied domestic wells**,** with water use estimated through regional per capita coefficients.
- Regional coefficients are based on Brown and Caldwell (1984) and adjusted with updated assessments.

- Self-supplied domestic population is determined by subtracting public water system (PWS) users from the total county population.
- Provides method for converting estimated daily per capita use into annual acre-feet withdrawals.

Oklahoma

Methods for Estimating Locations of Housing Units Served by Private Domestic Wells in the United States Applied to 2010. *Journal of the American Water Resources Association*, 57(5), 828–843. https://doi.org/10.1111/1752-1688.12937

This study presents a methodology to estimate the locations and densities of housing units reliant on private domestic wells across the United States, using data from the 2010 census. The authors developed a model that integrates housing unit density with state well logs to produce high-resolution maps at the census block group level. The results indicate that approximately 23 million housing units, representing 17% of the U.S. population, depend on private domestic wells for their water supply. This approach provides a significant improvement over previous estimates by offering more detailed spatial distribution data, which is crucial for water resource management and contamination risk assessment.

Key Facts:

- Combines 2010 Census housing data with state well logs to map the distribution of housing units served by private domestic wells.
- Produces detailed maps at the census block group level, improving the granularity of private well distribution estimates.
- Highlights a 50% increase in households using private wells since 1990, reflecting a growing reliance on self-supplied water sources.
- Introduces metrics such as the groundwater exploitation index to evaluate the balance between recharge and withdrawals.

Oklahoma Water Resources Board. (2012) Oklahoma Comprehensive Water Plan 2012 Update: Water Supply Permit Availability Report. Oklahoma Water Resources Board. https://oklahoma.gov/content/dam/ok/en/owrb/documents/water-planning/ocwp/OCWPWaterSupplyPermitAvailability.pdf

This report presents a detailed assessment of Oklahoma's water supply and the availability of permits for water usage. It examines current water demands, future projections, and the capacity of existing water sources to meet these needs. The document also outlines the regulatory processes governing water permits, highlighting challenges and recommendations for sustainable water management in the state.

Key Facts:

- It highlights the process for allocating groundwater rights as an equal proportionate share (EPS) per acre, similar to what was described in your key facts.

- The OWRB determines the maximum annual yield for each groundwater basin to ensure sustainable use over 20 years, allocating water as an equal proportionate share per acre. In basins without an established yield, temporary permits allow up to 2 acre-feet of groundwater withdrawal per acre annually.

It also describes how withdrawals are estimated using permitting data and hydrologic studie**s** to monitor basin health and ensure sustainable water use.

Oklahoma Water Resources Board. (2012). Oklahoma Comprehensive Water Plan Executive Report. https://oklahoma.gov/content/dam/ok/en/owrb/documents/water-planning/ocwp/OCWPExecutiveRpt.pdf

This report provides an overview of Oklahoma's water resources, outlining water availability, projected demands, and key management strategies to address sustainability challenges. It evaluates groundwater and surface water interactions**,** infrastructure needs, and policy recommendations to ensure long-term water security. The plan emphasizes regional water shortages and conservation efforts, particularly in rural and urban supply planning.

Key Facts

- Per Capita Water Use Models: Domestic well withdrawals are estimated using population size and average per capita water consumption rates, derived from public water supply data and rural household surveys. These values are adjusted to reflect regional variations in water use behavior.
- Land Use and Well Density Correlations: The study maps domestic well locations and correlates well density with land use classifications to estimate total groundwater extractions. Areas with higher rural well densities are assumed to have greater self-supplied water use, helping refine regional demand estimates.
- Comparisons with Metered Systems: Benchmarks estimated domestic well withdrawals against data from public water systems to improve accuracy.
- Water Supply Planning: Evaluates the impact of unmetered withdrawals on groundwater sustainability and future water management policies.

Osborn, N. I. (2009). Arbuckle-Simpson Hydrology Study: Final Report to the U.S. Bureau of Reclamation in accordance with Cooperative Agreement No. 03FC601814. *Oklahoma Water Resources Board*. https://oklahoma.gov/content/dam/ok/en/owrb/documents/science-and-research/hydrologic-investigations/arbuckle-simpson-final-USBR-report.pdf

This study conducted a comprehensive hydrogeologic assessment of the Arbuckle-Simpson aquifer in Oklahoma to determine sustainable groundwater withdrawal rates. A multidisciplinary approach, integrating geological characterization, hydrological monitoring, geochemical analysis, and numerical modeling, was employed to estimate groundwater availability and its interaction with surface water.

Key Facts:

- Hydrogeologic Characterization: Mapped aquifer properties, including stratigraphy, fault structures, permeability variations, and fracture networks, to understand groundwater movement and storage.
- Developed a transient numerical groundwater/surface-water flow model to simulate groundwater withdrawals and evaluate their effects on baseflow in connected streams and springs.
- Modeled various groundwater withdrawal scenarios to assess impacts on aquifer storage and streamflow, informing sustainable yield recommendations.