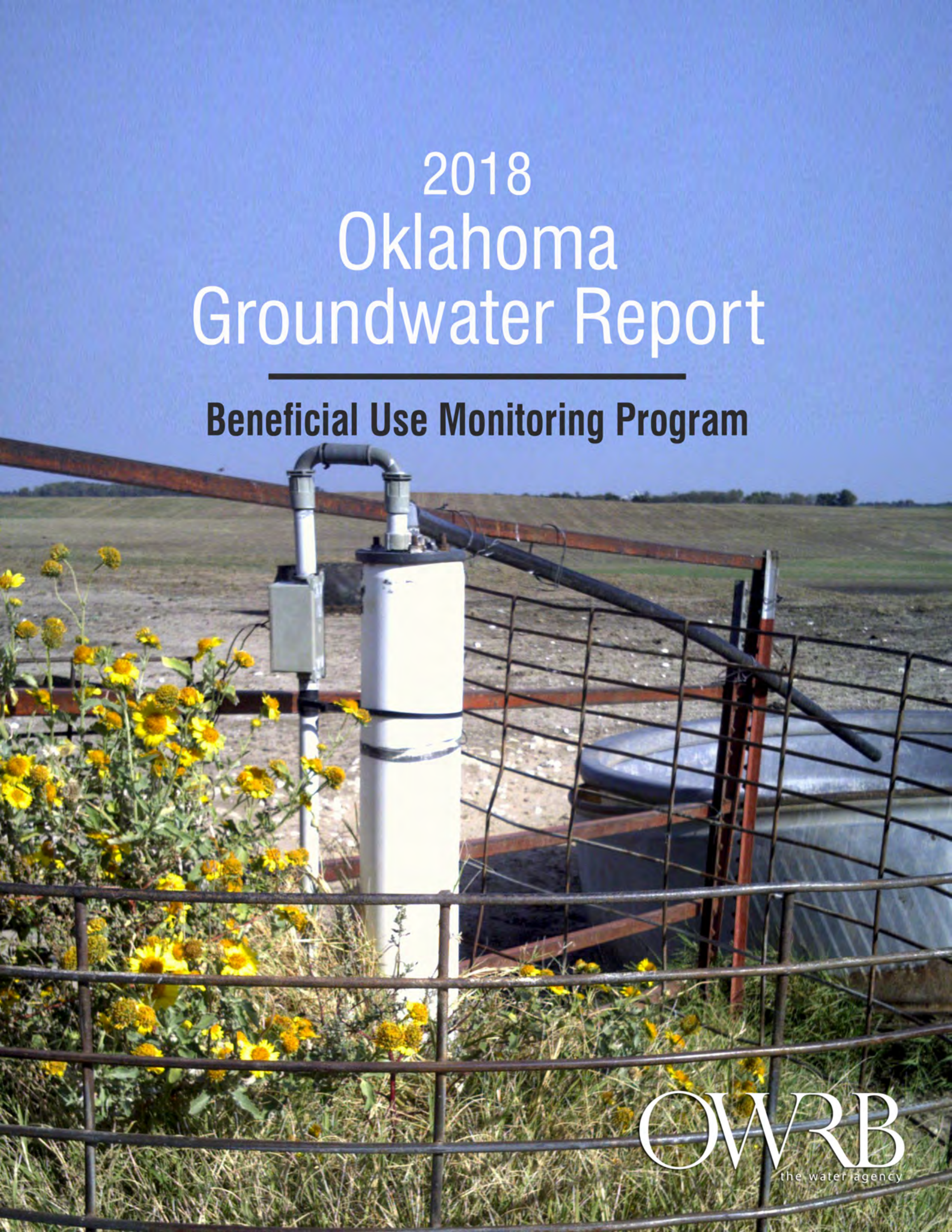
2018 Oklahoma Groundwater Report

Beneficial Use Monitoring Program



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Executive Summary

The goal of the Groundwater Monitoring and Assessment Program (GMAP) is to determine baseline water quality and quantity against which future changes can be measured, detect and quantify water quality and quantity trends, assess beneficial use support as appropriate, and apply collected data towards the establishment of beneficial use criteria for the State's groundwater resources as well as strengthen existing beneficial use criteria.

It is the intent of the Oklahoma Water Resources Board (OWRB) to advance concepts and principles of the Oklahoma Comprehensive Water Plan (OCWP). Consistent with a primary OCWP initiative, this and other OWRB technical studies provide invaluable data crucial to the ongoing management of Oklahoma's water supplies as well as the future use and protection of the state's water resources. Oklahoma's decision-makers rely upon this information to address specific water supply, quality, infrastructure, and related concerns. Maintained by the OWRB and updated every 10 years, the OCWP serves as Oklahoma's official long-term water planning strategy. Recognizing the essential connection between sound science and effective public policy, incorporated in the Water Plan is a broad range of water resource development and protection strategies substantiated by hard data – such as that contained in this report – and supported by Oklahoma citizens.

Beneficial Use Monitoring Program Goal

To synchronize Oklahoma's monitoring efforts related to water quality, the State Legislature appropriated funds in 1998 to create the Beneficial Use Monitoring Program (BUMP) under direction of the OWRB, which maintains Oklahoma's Water Quality Standards (WQS). The goal of the BUMP is to document beneficial use impairments, identify impairment sources (if possible), detect water quality trends, provide needed information for the Oklahoma Water Quality Standards (OWQS) and facilitate the prioritization of pollution control activities.

The BUMP exists as a result of the vital economic and social importance of Oklahoma's lakes, streams, wetlands, and aquifers and the associated need for their protection and management. Surface water data has been collected and analyzed following procedures outlined in Use Support Assessment Protocols (USAP), developed by the OWRB in collaboration with Oklahoma's environmental agencies. Specifically, USAPs establish a consistent and defensible method to determine if beneficial uses assigned for individual waters through OWQS are supported or not supported. If the BUMP report indicates that a designated beneficial use is not supported measures must be taken to restore the water quality. As groundwater does not currently have USAP's, the data are analyzed and compared to USEPA drinking water guidelines and benchmarks. Data generated by the program are collected in a scientifically defensible manner using industry accepted standards, so that beneficial use assessments can ultimately be performed and potential development of robust numerical groundwater quality standards can be explored.

Data collected from the GMAP will serve to establish additional beneficial use criteria for the State's groundwater resources, strengthen existing criteria, detect water quality and quantity trends, and promote more accurate groundwater use guidelines for the major aquifers of the State. This report interprets current Oklahoma groundwater data collected as part of the State's first aquifer-based, long-term funded holistic groundwater quality and quantity monitoring program. As such, the GMAP joins established surface water monitoring programs as a vital component of the BUMP. As the program matures, the BUMP report is sure to continue to be one of the most important documents published annually in Oklahoma.

Beneficial Use Monitoring Program Components

- **Groundwater Monitoring and Assessment Program (GMAP)** – This program was funded by the Oklahoma Legislature based on recommendations of the 2012 Update of the Oklahoma Comprehensive Water Plan. These additional monies were utilized to restore funding levels of the Beneficial Use Monitoring Program as well as to implement the new groundwater program. The program prioritizes efforts on Oklahoma's 22 major groundwater aquifers, with the baseline phase completed at the conclusion of 2017 and long-term trend monitoring scheduled to begin in 2019. The baseline period focused on 4-6 aquifers per year, beginning in 2013, and assessed concentrations of nutrients, metals and major ion species. The final baseline network comprised 662 wells in major aquifers with an additional 87 wells in minor aquifers. OWRB also maintains a statewide groundwater level measurement program comprising around 904 wells measured annually, 290 wells measured seasonally, and 33 continuous water level recorders.
- **Monitoring Rivers & Streams** - The OWRB is currently monitoring approximately eighty-four (84) stations on a 6-week rotation. Fixed station monitoring is based largely upon the eighty-four (84) planning basins as outlined in the Oklahoma Comprehensive Water Plan (OCWP). In general, at least one (1) sample station was located at the terminal end of each of the planning basins. The OWRB also conducts sampling on 25-30 probabilistic monitoring stations annually.
- **Fixed Station Load Monitoring** - The OWRB is currently working with several partners including the United States Geological Survey (USGS), US Army Corp of Engineers (USACE), Grand River Dam Authority (GRDA), and other partners to conduct flow monitoring on all of our fixed station sites that are not part of the Oklahoma/USGS Cooperative Gaging Network. This cooperative effort allows for loadings to be calculated, trends to be assessed statewide, and provides much needed data for the Use Support Assessment process. Along with the USGS cost share program, Oklahoma's 319 program and the 303(d)-process will drive sample site locations associated with this task.
- **Fixed Station Lakes Monitoring** – As part of BUMP, the OWRB conducts sampling on lakes and reservoirs across the State of Oklahoma. To accomplish this task, the OWRB has taken a fixed station approach for the lakes monitoring program. This design allows the state's objectives to be met as well as ensure various sized waterbodies are represented adequately. The survey population includes all lakes above 50 surface acres, which encompasses approximately 206 different waterbodies. The population is then stratified into two groups – lakes greater than 500 surface acres and those below 500 surface acres. The greater than 500 surface acres group includes 68 lakes, of which approximately one-fifth are monitored annually (quarterly samples). They are then monitored again during a subsequent year in the 5-year rotation, so that each lake greater than 500 surface acres is sampled 2 non-consecutive years during each 5 year rotation. The lakes managed by our

Federal partners, the USACE and Bureau of Reclamation (BOR) are included in the 68 large multipurpose lakes. Additionally, ten lakes of less than 500 surface acres are sampled annually (quarterly samples) over the 5 year sample frame. All lakes monitored have either the PPWS or SWS designation. Many of these smaller lakes have not been sampled historically through BUMP and include small municipal water supplies.

- **Intensive Investigations** - If beneficial use impairment is identified or suspected, then all appropriate state agencies will be alerted and an investigation will be initiated to confirm if beneficial use impairment is occurring. If routine monitoring cannot definitively identify impairments, then an intensive study may be undertaken and if impairment is present, the source of the impairment will be identified if possible.

Program History/Overview

Historically, groundwater monitoring in Oklahoma has focused its resources and efforts on compliance monitoring, resource conservation and groundwater protection through and by several Oklahoma state environmental agencies (Oklahoma Department of Agriculture, Food and Forestry, Oklahoma Conservation Commission, Oklahoma Corporation Commission, Oklahoma Department of Mines, Oklahoma Department of Environmental Quality and OWRB).

Enforcement and oversight of groundwater regulatory programs is of vital importance to the ongoing efforts to protect and manage, and if necessary mitigate, affected groundwater resources from regulated contamination sources. Some of these programmatic areas include source water protection, underground injection control, water produced or trapped in mines, water produced from oil and gas production, waste water lagoons, hazardous materials storage, fuel storage tanks and lines, water quality standards, groundwater rights permitting, and groundwater technical studies governing water rights permitting.

The Groundwater Monitoring and Assessment Program is not a regulatory program that targets a land use category or water use sector. Rather, the program is designed to characterize each aquifer utilizing existing groundwater wells drilled by licensed well drillers, records of which are maintained in the OWRB’s online database. Based on defined areal and vertical aquifer boundaries, a spatially allocated, probabilistic (randomized) draw of wells within each aquifer yields monitoring sites that can be used to characterize the aquifer as whole.

Introduction

Protecting Oklahoma's valuable water resources is essential to maintaining the quality of life for all Oklahomans. Used for a myriad of purposes—such as irrigation, hydropower, public/private water supply, navigation, and a variety of recreational activities—the state's surface and groundwater resources provide enormous benefits to Oklahoma from both an economic and recreational standpoint.

It is estimated that Oklahoma's aquifers store approximately 386 million acre-feet of groundwater which fuels the state's economy, serving as supply for thousands of municipalities, rural water districts, industrial facilities, and agricultural operations. According to the 2012 update of the Oklahoma Comprehensive Water Plan (OCWP), groundwater represents the primary water supply for approximately 300 cities and towns and comprises 43 percent of the total water used in the state each year. Groundwater resources also supply approximately 90% of the state's irrigation needs, and around 8% of Oklahoma's citizens obtain their drinking water from private wells.

Oklahoma works to protect and manage its water resources through a number of initiatives, with the Oklahoma Water Quality Standards (OWQS) serving as the cornerstone of the state's water quality management programs. The Oklahoma Water Resources Board (OWRB) is designated by state statute as the agency responsible for promulgating water quality standards and developing or assisting the other environmental agencies with implementation framework. All state environmental agencies are currently required to implement OWQS within the scope of their jurisdiction through the development of a WQS Implementation Plan (WQSIP) specific for their agency. Protecting our waters is a cooperative effort between many state agencies and because the OWQS are utilized by all state environmental agencies and represent a melding of both science and policy, they are an ideal mechanism to manage water quality, facilitate best management practice initiatives, and assess the effectiveness of our diverse water quality management activities.

The OWQS are housed in Oklahoma Administrative Code 785:45 and consist of three main components: beneficial uses, criteria to protect beneficial uses, and an anti-degradation policy. An additional component, which is not directly part of the OWQS but necessary for resource protection, is a monitoring program. A monitoring program is required in order to ensure that beneficial uses are maintained and protected. Beneficial use designations are limited in groundwater due in part to lack of long-term water quality data. Data collected from the OWRB's Groundwater Monitoring and Assessment Program (GMAP) was funded to address high-priority recommendations in the 2012 Update to the OCWP. These data may serve to establish additional beneficial use criteria for the State's groundwater resources, as well as to strengthen existing criteria.

Work to be performed towards development and implementation of the critical fourth component of the OWQS program, monitoring, is the subject of this report. All sampling activities described and conducted as part of this program were consistent with the USGS National Field Manual for the Collection of Water-Quality Data.

Background & Problem Definition

The State of Oklahoma has historically had numerous monitoring programs conducted by several state and federal agencies with varying degrees of integration and coordination with other state, municipal, or federal programs. This document describes sampling activities of the first aquifer-based, long-term funded holistic groundwater quality and quantity monitoring program to be implemented in the State of Oklahoma that examines the groundwater resources of the state's aquifers outside the context of the state's regulated entities. The GMAP joins ongoing efforts on lakes and streams across Oklahoma as part of a comprehensive, long-term, statewide Beneficial Use Monitoring Program (BUMP).

Beneficial Use and Monitoring Program Overview

The goal of the BUMP is to detect and quantify water quality trends, document and quantify impairments of assigned beneficial uses, identify pollution problems before they become a pollution crisis, and provide needed information for the OWQS. Data collected from the Groundwater Monitoring and Assessment Program will serve to determine a baseline of water quality and quantity against which future changes can be measured, establish beneficial use criteria for the State's groundwater resources, strengthen existing criteria, detect water quality and quantity trends, and promote more accurate groundwater use guidelines for the major aquifers of the State. The goal of the GMAP is to characterize ambient conditions in Oklahoma's aquifers. In other words, this program is not intended for compliance, to track the sources of pollution or to inform pollution control, but rather, it is intended to establish the background ambient aquifer conditions.

The BUMP include both groundwater and surface water components. Within the BUMP, the GMAP prioritizes water level and water quality monitoring on Oklahoma's 22 major groundwater aquifers, and surface water programs include the monitoring of rivers, streams and lakes through a variety of fixed station and probabilistic monitoring designs. For a more complete description of these programs, please go to the "Monitoring and Assessment" section at *http://owrb.ok.gov*.

Groundwater Monitoring & Assessment Program

The Oklahoma state legislature adopted the 2012 update of the Oklahoma Comprehensive Water Plan (OCWP) and ultimately provided 1.5 million dollars toward expanding Oklahoma's surface and groundwater monitoring capacity. This funding enabled the establishment of a holistic Groundwater Monitoring & Assessment Program (GMAP). This is the first aquifer-based, long-term groundwater monitoring program to be implemented in the state.

Groundwater Resources of Oklahoma

Groundwater is water that has percolated downward from the surface, filling voids or open spaces in rock formations. The underground zone of water saturation begins at the point where subsurface voids are full or saturated. An aquifer is a subsurface rock formation capable of yielding groundwater to wells. In Oklahoma, aquifers range in geologic age from Cambrian (570 million years) to Quaternary (1.6 million years to present).

Oklahoma's aquifers are of two basic types: bedrock aquifers that are consolidated to semi-consolidated rock formations composed of sandstone, shale, limestone, dolomite, and gypsum; and, alluvial aquifers that are unconsolidated and composed of a heterogeneous mixture of sand, gravel, silt and clay. The OWRB defines major bedrock aquifers as those that yield an average of at least 50 gpm (gallons per minute) of water to wells, and major alluvial aquifers as those yielding, on average, at least 150 gpm. Groundwater occurs both at great depths and near the surface of the earth. In Texas County, Oklahoma, groundwater depths approach 400 feet below land surface. Conversely, at certain times of the year, depth to water in alluvial aquifers may occur less than a foot below land surface. Springs, seeps and artesian wells reflect groundwater discharging to the land surface.

Groundwater quality is derived from the type of rock and minerals that compose the groundwater system, the solubility of the minerals in the rock, and the amount of time water has been in contact with the rock. Important controls include atmospheric inputs (gases and aerosols), mineral weathering from rock-water interaction, biochemical processes associated with the life cycles of microbes, plants and animals, acidity and temperature, subsurface oxidation-reduction reactions, and cultural effects resulting from human activity.

Program Structure

The GMAP prioritizes efforts on the 10 major bedrock and 12 major alluvial aquifers identified by OWRB, along with some associated minor aquifers (Table 1). The 5-year baseline monitoring period assessed concentrations of nutrients, metals and major ion species to characterize regional groundwater quality and levels. At the conclusion of the baseline monitoring period, there were 654 wells sampled from major aquifers in the statewide groundwater quality network, with an additional 87 wells in minor aquifers (Figure 4, Table 4).

Table 1. Aquifers sampled for GMAP.

Alluvial aquifers		Bedrock aquifers	
ARKS	Arkansas River	**ADVM**	Ada-Vamoosa
BNCR	North Canadian River	**ALRS**	Antlers
CNDN	Canadian River	**ABSMP**	Arbuckle-Simpson
CMRN	Cimarron River	**ABTH**	Arbuckle-Timbered Hills
ENID	Enid Isolated Terrace	**ELKC**	Elk City
GRTY	Gerty Sand	**GSWF**	Garber-Wellington
NFRR	North Fork of the Red River	**OGLL**	Ogallala
RED	Red River	**RBDX**	Roubidoux
SFAR	Salt Fork of the Arkansas River	**RSPG**	Rush Springs
SFRR	Salt Fork of the Red River	**BOON**	Boone (minor)
TILL	Tillman Terrace	**DAKD**	Dakota-Dockum (minor)
WASH	Washita River	**DCBG**	Blaine (water level only)
WOLF	Wolf Creek (minor)		

Additionally, OWRB's annual groundwater level measurement program has been in place for approximately 50 years stemming from a need to support hydrologic studies to determine maximum annual yields of fresh groundwater basins and to monitor the effects of permitted groundwater withdrawals and drought on aquifer storage. These data are used to evaluate aquifer response to climatic conditions, land use, and water use; determine aquifer storage for allocation of water rights; conduct aquifer studies and model groundwater systems; and map areas of water level change in the High Plains aquifer. The water level network in the mid-late 1980s was composed of over 1,000 observation wells and nearly all major aquifers had some representation of observation wells. However, due to lack of dedicated funding and personnel for operation and maintenance, the network had shrunk to 530 unevenly distributed wells at the time of the GMAP implementation. Since the GMAP implementation the groundwater level network has nearly doubled in capacity from around 530 to 904 wells and has been spatially redistributed (Figure 1). Also over the 5-year baseline period, the OWRB installed 33 continuous water level recorders to obtain hourly measurements. These measurements are more sensitive for the detection of seasonal changes (brought on by drought or variable climate conditions) compared to those obtained by manual measurements (Figure 2. Sites with OWRB continuous water level recorders installed.).

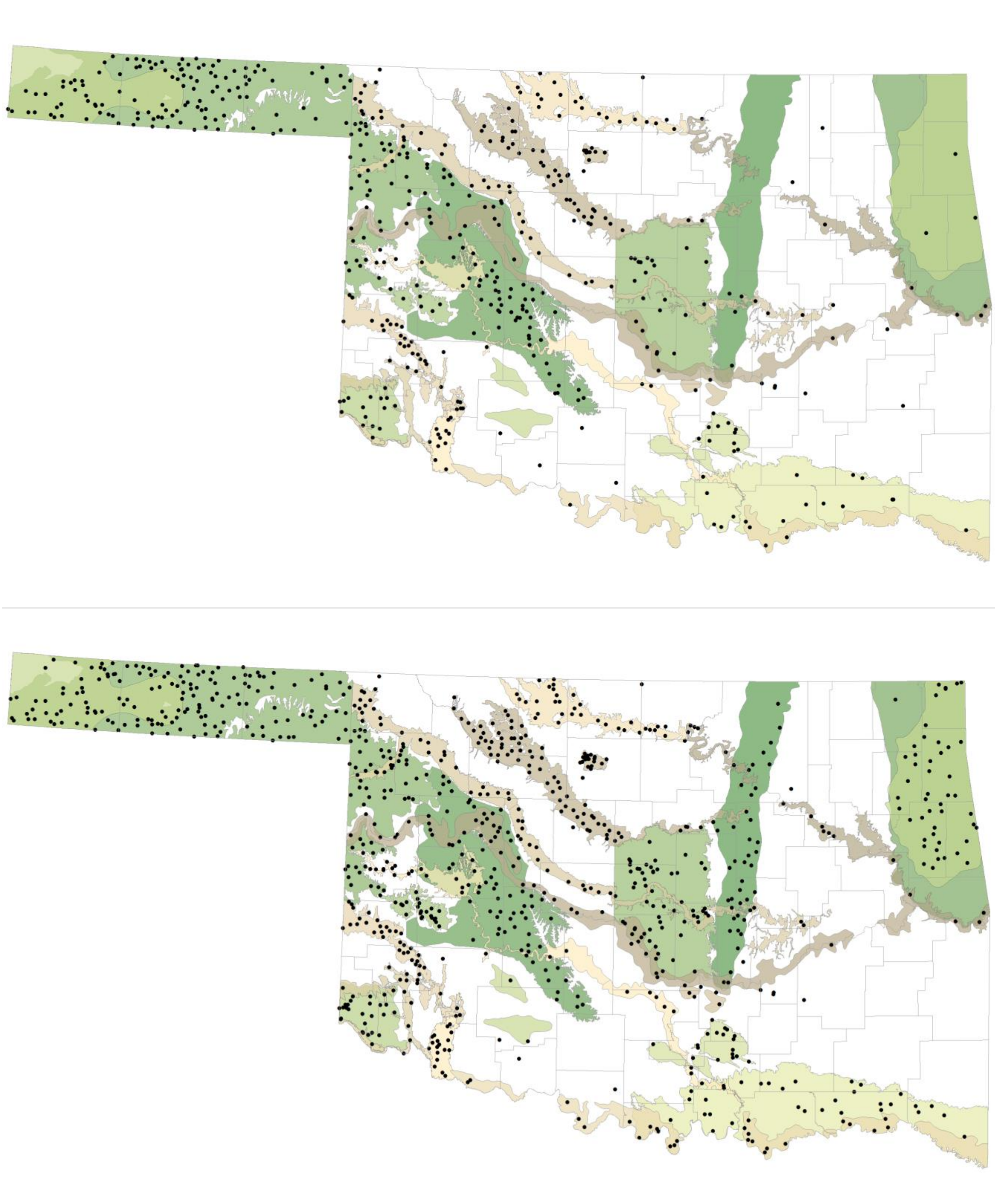


Figure 1. OWRB groundwater level network before (2013; top) and after (2018; bottom) the GMAP implementation.

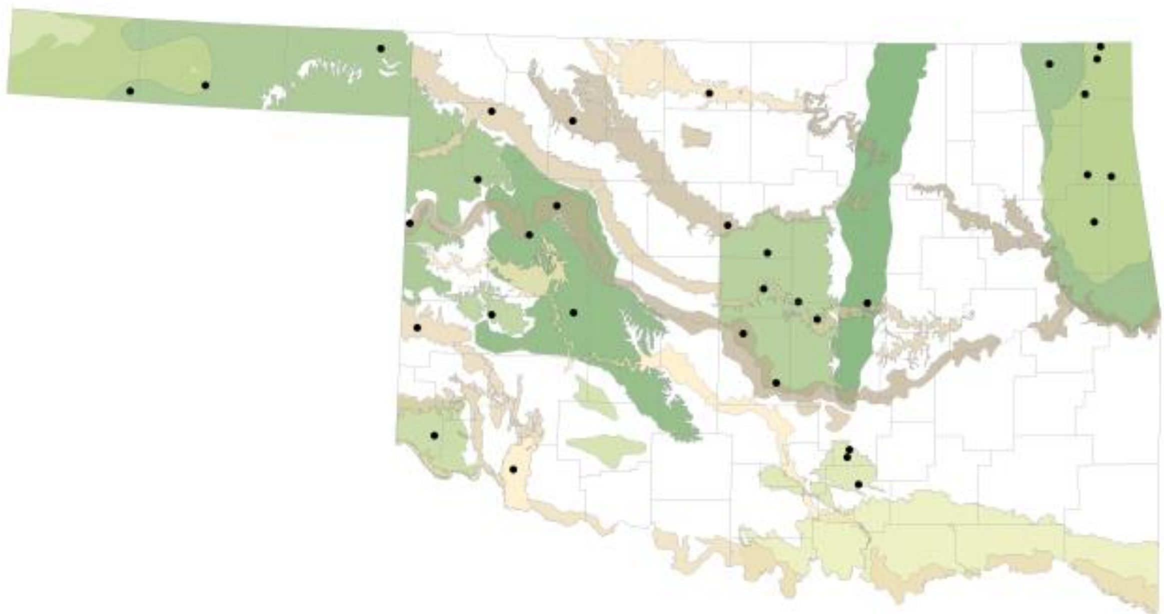


Figure 2. Sites with OWRB continuous water level recorders installed.

Since 2004, the OWRB has collaborated with the Oklahoma Climatological Survey (OCS) to drill groundwater level observation wells at 9 Oklahoma Mesonet Stations. These wells are equipped with down-hole continuous recorders for hourly depth to water measurements (Figure 2). These groundwater level data are synced with the Mesonet station that captures real-time climate data on 20 variables including precipitation, soil moisture, air temperature, and barometric pressure. Continuous, simultaneous capture of day to day weather phenomena and long-term climate events in association with groundwater levels will allow researchers to study the relationships between changing climate and groundwater recharge and storage.

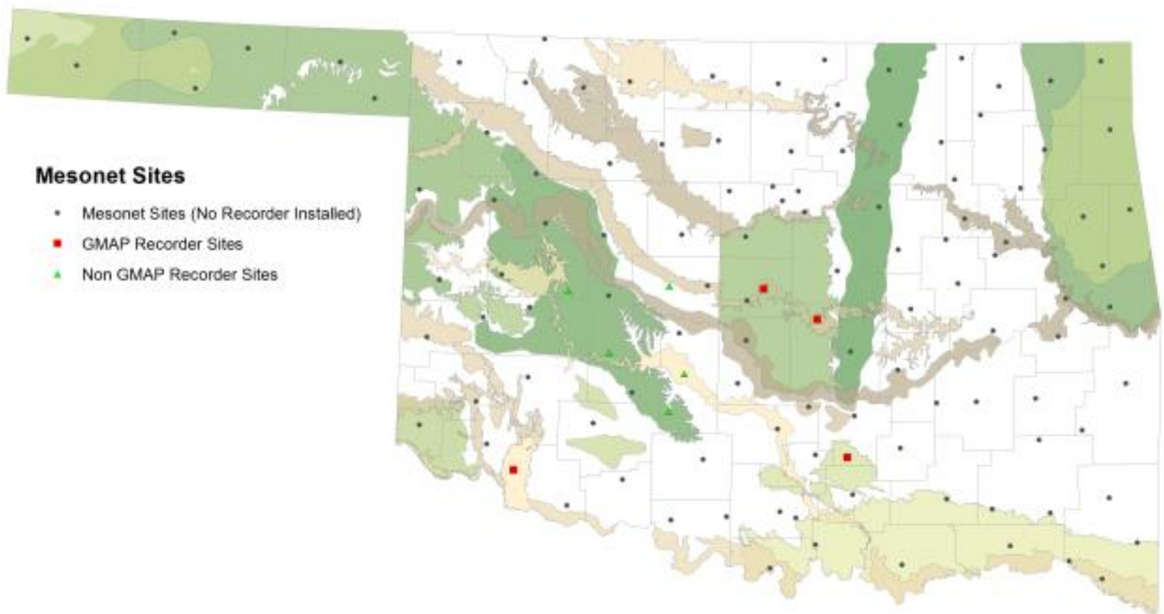


Figure 3. Mesonet stations. Red squares depict sites with installed GMAP recorders.

Methods and Materials

Sample Strategy and Site Selection

Sampling sites were derived from the Oklahoma Water Resources Board's (OWRB) licensed well drillers' well log database, which houses over 190,000 completion reports of groundwater and monitoring wells constructed within the state. Well selection criteria required: 1) that the well be located within the geographic outcrop or subcrop of the aquifer; 2) that the well information include details of the borehole lithology; 3) that the screened or open hole interval of the well bore was completed in at least 75% of the subject aquifer and 4) that wells drilled for the purpose of monitoring regulated point sources (e.g., around waste water retention lagoons) be excluded. Additionally, a target density was set with the goal of spatial representation to achieve a sample population proportional to the size of the aquifer (Table 2). The resulting lists of wells were provided to the Western Ecology Division of the U.S. Environmental Protection Agency (EPA) where a spatially balanced, randomized tessellation stratified survey design was used to select wells for each aquifer in the program. This survey design type was chosen to yield data representing the general water quality of each aquifer using a population of only an existing network of available wells.

Once landowners gave permission for access, reconnaissance visits to each site were made to verify the correct well and to further assess the suitability for inclusion into the program based on details such as existing plumbing, current use, and measurement access. Wells were preliminarily screened based on specific conductance and hardness to ensure representativeness of formation water. If the well was deemed suitable, site information, including detailed elevation information, was entered into a Trimble GeoExplorer series handheld GPS unit.

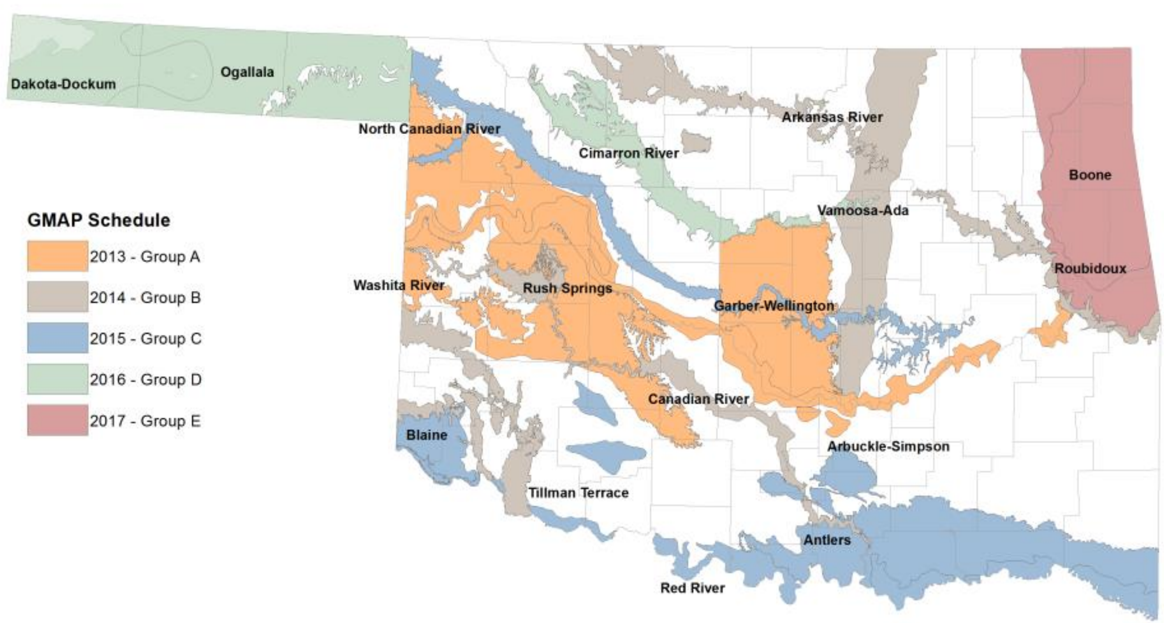


Figure 4. GMAP implementation schedule.

Table 2. Target sample networks based on aquifer areal extent.

Areal Extent Category	Sample Site Well Density	Sample Sizes Generated
> 5000 km^2	1 well per 150 km^2 (6 aquifers)	37 – 89
3001 – 5000 km^2	1 well per 100 km^2 (5 aquifers)	33 – 48
1501 – 3000 km^2	1 well per 75 km^2 (6 aquifers)	25 – 33
751 – 1500 km^2	1 well per 50 km^2 (2 aquifers)	16 – 19
≤ 750 km^2	2 aquifers	6 – 10

Sample Collection

Information gathered in the reconnaissance visits was used to ascertain the best sample collection methodology, which varied based on well type and well use. Sampling was two-part: water level measurement and water quality sampling. Water level measurements were taken with an electric or steel tape.

During water quality sampling, wells were purged of stagnant water when necessary to ensure formation water was being sampled. In all sampling scenarios, water quality parameters were monitored with a YSI EXO sonde. Water was considered to be representative of the formation when water quality parameters had stabilized to within the stated limits for 3 consecutive measurements.

- pH ± 0.2 Standard Units
- Specific Conductance: ± 3.0% of reading
- Dissolved Oxygen: ± 0.2 mg/L or 10%

Samples collected were filtered using an in-line, 45 µm filter, preserved and stored on ice. Field analyses of alkalinity and hardness were performed using EPA-equivalent Hach field methods. With the exception of *in situ* parameters, The ODEQ State Environmental Laboratory, the Robert S. Kerr Environmental Research Center (EPA) or Accurate Laboratories ran analyses for all parameters on all samples.

Gloves were worn while sampling and “Clean Hands, Dirty Hands” protocol was followed. All sampling equipment was decontaminated after every site with a Liquinox solution and deionized water.

Groundwater Constituents

The natural composition and character of groundwater is highly influenced by the rock and sediments it comes into contact with; therefore, water quality will differ between aquifers due to geologic and mineralogical differences. Constituents sampled in the GMAP’s baseline were chosen in part because they are naturally occurring substances in groundwater (Table 3). These water quality parameters provide descriptions of general water chemistry as depicted by major ion concentrations, physical characteristics (hardness & pH), salinity and overall mineralization. Some additional parameters address known water quality concerns in some of the state’s aquifers such as nitrate-N, chloride, sulfate, and arsenic levels. Several minor and trace elements were also included because the EPA had established primary or secondary drinking water maximum contaminant level and therefore designates said element as a key water quality parameter of interest. Lastly, some constituents (such as mercury) that have not been reported with substantial frequency as concerns in Oklahoma's groundwater were included in the baseline survey to characterize their occurrence.

Some explanations follow on how the State of Oklahoma and the USEPA regard these sampled constituents, along with some generalizations on how they are reported here. The OWRB designates a domestic beneficial use for groundwater in Oklahoma with total TDS concentrations below 3,000 mg/L. The EPA has set up guidelines used to evaluate drinking water provided by public systems, with thresholds for certain constituents (last issued in 2012; Table 3). A suite of parameters sampled in the GMAP is regulated for health reasons. These have an enforceable Maximum Contaminant Level (MCL) threshold over which water is not considered safe for human consumption. A separate suite of parameters is regulated for aesthetic reasons such as taste, color, and odor. These secondary maximum contaminant levels (SMCL) are not enforceable and do not represent a safety consideration. In addition, the EPA has issued health advisories for a few constituents that do not have MCLs. Some parameters sampled in the GMAP are not regulated for drinking water, although cobalt, molybdenum, and vanadium are included on the EPA Final Contaminant Candidate List 4 (manganese, which has a SMCL and a nonregulatory health advisory, is also slated for review). Wells sampled during the GMAP were of mixed uses and included both wells intended for human consumption and those not. In the presentation of this data, the average of the entire sampling is compared against these thresholds, regardless of well use. Of note is that nitrate+nitrite generally presents as nitrate in most ambient environmental conditions, so the MCL for nitrate was applied for this combination. For simplicity of reading, nitrate+nitrite samples will hereafter be referred to as nitrate samples (reported as nitrate-N), but the two were always tested together. Furthermore, groundwater samples collected for the GMAP were filtered in the field, resulting in dissolved concentrations of constituents. The EPA issued thresholds are for total concentrations, and total concentrations for any given constituent may be higher for an unfiltered sample from the same source.

Table 3. Parameters sampled during GMAP baseline, their chemical category, and drinking water guidelines.

Parameter	Category	Laboratory Analytic Method	USEPA MCL	USEPA SMCL	USEPA Health Advisory
Hardness	General Chemistry	-	-	-	-
Alkalinity	General Chemistry	-	-	-	-
pH	General Chemistry	-	-	6.5 - 8.5	-
Dissolved Oxygen	General Chemistry	-	-	-	-
Specific Conductance	General Chemistry	-	-	-	-
Orthophosphate	General Chemistry	-	-	-	-
Total Dissolved Solids	General Chemistry	SM2540-C	-	500 mg/L	-
Nitrate+Nitrite as N	Nutrient	353.2	10 mg/L	-	-
Ammonia as N	Nutrient	350.1	-	-	30 mg/L
Phosphorus	Nutrient	365.1	-	-	-
Sulfate	Mineral	300.0	-	250 mg/L	500 mg/L
Chloride	Mineral	300.0	-	250 mg/L	-
Bromide	Mineral	300.0	-	-	-
Fluoride	Mineral	300.0	4 mg/L	2 mg/L	-
Deuterium*	Stable isotope	RSKSOP-334 v. 0			
Oxygen-18*	Stable isotope	RSKSOP-334 v. 0			
Aluminum, Dissolved	Metal/Trace Element	200.8	-	50-200 µg/L	-
Antimony, Dissolved	Metal/Trace Element	200.8	6 µg/L	-	-
Arsenic, Dissolved	Metal/Trace Element	200.8	10 µg/L	-	-
Barium, Dissolved	Metal/Trace Element	200.8	2,000 µg/L	-	-
Beryllium, Dissolved	Metal/Trace Element	200.8	4 µg/L	-	-
Boron, Dissolved	Metal/Trace Element	200.7	-	-	6,000 µg/L
Cadmium, Dissolved	Metal/Trace Element	200.8	5 µg/L	-	-
Calcium, Dissolved	Mineral	200.7	-	-	-
Chromium, Dissolved	Metal/Trace Element	200.8	100 µg/L	-	-
Chromium VI, Dissolved*	Metal/Trace Element	218.6	-	-	-
Cobalt, Dissolved	Metal/Trace Element	200.8	-	-	-
Copper, Dissolved	Metal/Trace Element	200.8	1,300 µg/L	1,000 µg/L	-
Iron, Dissolved	Metal/Trace Element	200.7	-	300 µg/L	-
Lead, Dissolved	Metal/Trace Element	200.8	15 µg/L	-	-
Lithium, Dissolved*	Metal/Trace Element	200.7			
Magnesium, Dissolved	Mineral	200.7	-	-	-
Manganese, Dissolved	Metal/Trace Element	200.8	-	50 µg/L	300 µg/L
Mercury, Dissolved	Metal/Trace Element	245.1	2 µg/L		-
Molybdenum, Dissolved	Metal/Trace Element	200.8	-	-	40 µg/L
Nickel, Dissolved	Metal/Trace Element	200.8	-	-	100 µg/L
Potassium, Dissolved	Mineral	200.7	-	-	-
Radium-226/228*	Isotope	Georgia Tech	5 pCi/L	-	-
Selenium, Dissolved	Metal/Trace Element	200.8	50 µg/L	-	-
Silica, Dissolved	Mineral	200.7	-	-	-
Silver, Dissolved	Metal/Trace Element	200.8	-	100 µg/L	100 µg/L
Sodium, Dissolved	Mineral	200.7	-	-	-
Strontium, Dissolved*	Metal/Trace Element	200.7			4,000 µg/L
Thallium, Dissolved*	Metal/Trace Element	200.8	2 µg/L	-	-
Thorium, Dissolved*	Metal/Trace Element	200.8			
Titanium, Dissolved*	Metal/Trace Element	200.7			
Uranium, Dissolved	Metal/Trace Element	200.8	30 µg/L	-	-
Vanadium, Dissolved	Metal/Trace Element	200.8	-		-
Zinc, Dissolved	Metal/Trace Element	200.8	-	5,000 µg/L	2,000 µg/L

Methods, MCLs, SMCLs, and Health Advisories are reflective of the most recent methods used and levels reported as of the publishing date of this document. For a comprehensive list of methods used, please reference past GMAP reports.

*Not included in every year's analyses.

Data Management and Reporting

This report will describe the results of statewide baseline sampling and groundwater level measurement. More in depth discussions of water quality for individual aquifers, as well as summary sheets for each aquifer sampled, can be found on the OWRB's website (http://www.owrb.ok.gov/gmap). The Summary of Baseline Water Quality Results will: 1) reflect the general condition of the state's groundwater resources in terms of total dissolved solids (TDS), water type and overall mineralization; 2) review and summarize the major constituents of concern in Oklahoma's aquifers; 3) discuss a few of the more common constituents of concern in greater detail; and 4) review the water level data for various types of aquifers across a wide range of climate and planning regions.

Data Storage

Upon receipt of data from labs and field collection, data is migrated into the Ambient Water Quality Monitoring System (AWQMS). AWQMS is an online cloud-based database designed by Gold Systems to specifically to house environmental data. AWQMS is outfitted with checks to aid staff in inspecting for completeness of data before being imported. Once in the database, all other data related activities can take place, many of which can be completed by using built-in tools in the database itself.

Quality Assurance/Quality Control (QA/QC)

QA/QC for this data included replicate and blank samples to evaluate sampling procedure, parameter ratios to check water chemistry results, and analysis of statistical outliers. QA/QC will not be discussed in detail in this report. For a complete description of field QA/QC methods, please contact the Oklahoma Water Resources Board/Water Quality Programs Division at (405) 530-8800. For laboratory QA/QC methods please contact the Oklahoma Department of Environmental Quality/Customer Services Division at (405) 702-6100, the Robert S. Kerr Environmental Research Center at (580) 436-8500 or Accurate Labs at (405) 372-5300. Comprehensive QA/QC has been performed on all data collected and utilized for this report.

Data Analyses

Only descriptive statistics were reported for baseline samples, as the main objective for this data is to summarize statewide ambient water quality conditions. Statistical summaries and quality assurance checks were conducted using Microsoft Excel 2007-2010. Descriptive statistics on the baseline data were run on a per aquifer basis. Reported statistics include mean, standard error of the mean, median, minimum value, maximum value, 25^{th} percentile, and 75^{th} percentile. For data that was less than the laboratory reporting limit, half of the limit was used as the value for that well. For parameters that had over 75 percent of wells below reporting limit, statistics were not run.

Outliers were identified utilizing both twice the standard deviation and 1.5 times the parameter's inter-quartile range as threshold values. For parameters with over 50 percent of wells below reporting limit, identified outliers were investigated but not considered noteworthy since they were often within expected ranges. Original data reports were used to confirm that outliers were not due to data entry errors; field notes were used to confirm nothing unusual was happening in the area at the time of sampling. All outliers were kept unless an acceptable explanation was discovered as to why that data point was unusual (lithology, screen interval, sampling error, etc.).

Water type was determined through Piper plot diagrams. These were constructed with raw data using AquaChem version 5.1 software. Any spatial data used for presentation or analysis was conducted on ArcGIS 10.6.1 and ArcGIS Pro. Hydrographs were produced using Grapher and box plots were developed in R.

Data Presentation

Throughout this report data will be displayed in a variety of ways to help make sense of and holistically characterize groundwater quality in Oklahoma. Box-and-whisker plots provide a visual of how data is distributed on an aquifer by aquifer basis. These plots will categorize aquifers by aquifer type and will display the median, quartiles, and outliers as well as show how those data compare to criteria such as the EPA MCLs and EPA SMCLs. Data will also be displayed spatially on a map of Oklahoma with dots that are colored and scaled according to the presence of specific constituents in groundwater. Various hydrographs will be displayed in latter sections of the report to help understand how groundwater levels, and consequently, water quantity, has changed over time. In a hydrograph time is depicted on the x-axis and depth to water from the ground surface is represented on an inverted y-axis. This is so that a drop in groundwater levels corresponds with a downward trending line on the hydrograph. Hydrographs will be presented in a variety of time scales and groupings based on aquifer type and other geographic boundaries. Pie charts are also available to show the number of sites not detected, present and present and exceeding water quality standards for several key water quality parameters. Lastly, piper plots (described in detail in *Piper Plot Discussion* section) will help us determine the homogeneity and source of groundwater across Oklahoma.

Summary of Baseline Water Quality Results

Results of Groundwater Sampling Efforts

The GMAP baseline sampling and measurement efforts (2013-2018) provides a framework for envisioning groundwater data needs to supplement water resource planning, identify beneficial use status, trend analysis and research/special studies. The framework of existing sites with "new" gap wells will provide spatially balanced monitoring networks to make future assessments of trends in water quality and quantity in Oklahoma's major aquifers. The networks can be adapted to fit research initiatives or special studies proposed by internal or external partners. Over time, as trends in water quality occur or depletions of aquifer levels occur; water planners can use this information to project the utility of the groundwater resource for beneficial use and identify or project areas that will be become water deficient. The 6 year baseline survey resulted in the water quality assessment of 741 fresh water wells. The capacity of the state's long-term (historical) groundwater level network was more than doubled over this time frame to 904 wells. Of these wells, a 33 well continuous groundwater level monitoring network was established that captures hourly measurements in many of the state's major aquifers.

Table 4. GMAP sampling schedule and results.

Sampling year	Aquifers sampled		Number of wells sampled	Number of wells measured
Group A – 2013	Canadian River Garber-Wellington Ogallala-Northwest	Elk City Gerty Sand Rush Springs	203	299
Group B – 2014	Ada-Vamoosa Enid Isolated Terrace Salt Fork-Arkansas River Tillman Terrace	Arkansas River North Fork-Red River Salt Fork-Red River Washita River	179	224
Group C – 2015	Antlers (unconfined portion) Arbuckle-Timbered Hills North Canadian River Wolf Creek (minor)	Arbuckle-Simpson Blaine (water level only) Red River	142	185
Group D – 2016	Cimarron River Ogallala-Panhandle	Dakota-Dockum (minor)	152	194
Group E – 2017	Boone	Roubidoux	51	51
Supplementary Sites – 2018	Ada-Vamoosa Cimarron River Gerty Sand	North Fork-Red River Salt Fork-Red river Tillman Terrace	14	14
Total baseline (2013 – 2018)	Statewide		741	967

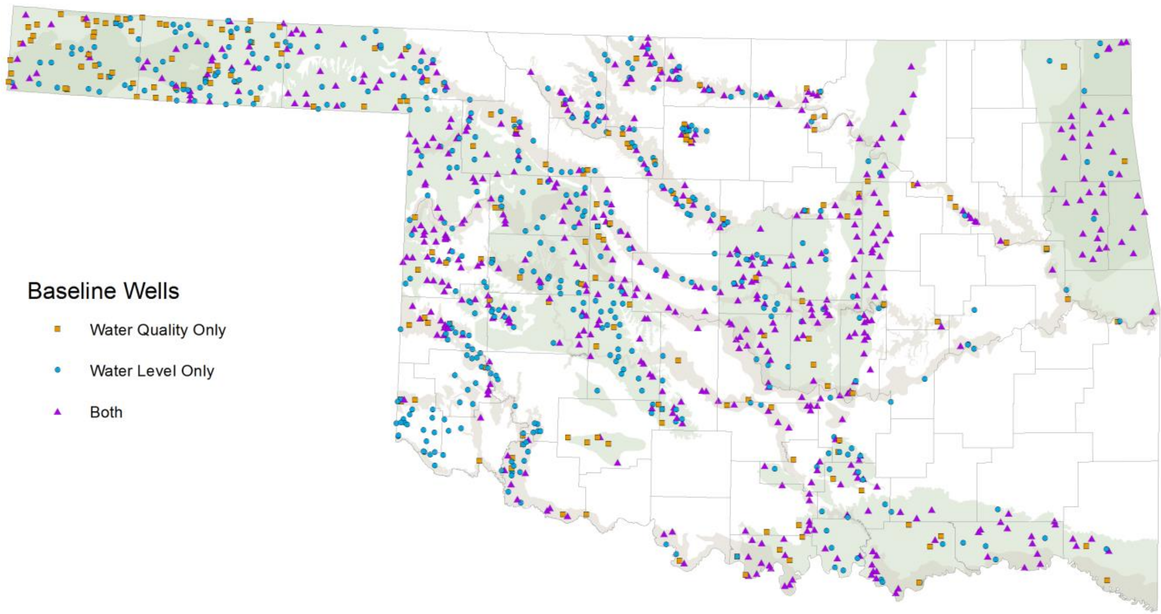


Figure 5. All sites sampled under the GMAP's baseline sampling period.

Summary of Water Quality (bedrock aquifers)

Natural groundwater quality across 8 of the eleven major bedrock aquifers show relatively low mineralization (median TDS < 500 mg/L) that describes groundwater suitable for beneficial use excepting situations where contaminants of concern occurred in individual samples. Locally in some of Oklahoma's bedrock aquifers, nitrates and trace elements (arsenic, chromium, selenium, uranium, manganese, and fluoride) were at levels that exceeded maximum contaminant levels MCLs for potable drinking water. The DCBG aquifer was not included in the GMAP's baseline water quality assessment. Groundwater in the DCBG is highly mineralized and not potable but is an important groundwater resource for irrigation. As part of a groundwater basin study that determines water storage for allocation of water rights, a special study of the groundwater quality of the DCBG will be investigated in 2019. Two other bedrock aquifers, the RBDX in NE Oklahoma and ABTH in SW Oklahoma could not be comprehensively assessed due to a lack of wells and/or irregular spatial distribution of wells over the their areal extent. For the small network of the ABTH (5 wells), all 5 wells exceeded the MCL for arsenic and 4 of the 5 wells exceeded the MCL for fluoride, TDS was > 500 mg/L in all wells. The quality of the RBDX documented by GMAP sampling (15 wells) was constrained primarily to Ottawa County and reflected water quality that supports beneficial use. Two wells however, exceed the MCL for Fluoride.

Summary of Water Quality (alluvial aquifers)

The water quality across alluvial aquifers was more variable than for the bedrock aquifers. Higher levels and variability of mineralization is geographically linked to factors including adjoining to Oklahoma's major river systems and crossing various geologic, vegetative and climate regions of the state. Bedrock influence on alluvial water quality is an important consideration. In western Oklahoma, underlying Permian bedrock formations containing compounds of salts (calcium/sodium + chloride/sulfate) are in direct contact with alluvial aquifers. Locally, water exchanges between the underlying bedrock and alluvial aquifers can impact water quality. As a consequence, TDS, sodium, chloride and sulfate tend to be elevated in western Oklahoma alluvial aquifers as compared to their eastern reaches and bedrock aquifers. The CNDN, WASH, ENID, NFRR and SFRR are aquifers that reflect regional variability and overall higher mineralization. Also, parameter exceedances of MCLs and SMCLs were more frequent in alluvial aquifers. Alluvial aquifers are naturally more vulnerable to anthropogenic contaminants than bedrock aquifers due to factors including shallow depth to water, sandy and permeable soils, unsaturated zones and higher recharge rates.

Piper Plot Discussion

Piper plots are tri-linear plots with the resulting water type being presented in the diamond portion. The left triangle displays the percentage of major cations (calcium, magnesium, sodium and potassium) and the right triangle displays the present percentage of major anions (bicarbonate, sulfate and chloride. Each well is plotted once in each triangle and the intersection of those two plots along the diagonal lines in the diamond determines the water type. These plots display the water chemistry of individual sample sites in terms of major cations and anions which proves useful for examining the variability or similarity in water chemistry across a data set. Additionally, piper plots can inform the origins of the mineral sources that yielded the particular water chemistry and can help to classify or group the data by water type (ex. calcium sulfate or magnesium, calcium-bicarbonate, etc.). Figure 6 displays the water types for all the alluvial and terrace aquifers in Oklahoma. Homogeneity is determined by observing how scattered or grouped results on a piper plot are. The tighter the grouping, the more homogenous the water, and conversely, the more scattered the grouping, the less homogenous the water. In alluvial-terrace aquifers, higher variability in water type occurs because these aquifers cross multiple hydrogeologic settings, climate and vegetation zones which can ultimately influence the quality of one sample as compared to another. In contrast, the piper plot of the ABSMP (Figure 7, left) reflect a uniform water chemistry derived from the dissolution of calcium and magnesium from the limestone and dolomitic rocks reflecting a calcium/magnesium bicarbonate water type. Figure 7 (right) shows that the ELKC water chemistry reflects a calcium/sodium bicarbonate groundwater. Figure 8 shows piper plot data of two parts of the OGLL aquifer. The Panhandle region is characterized by calcium/sodium-bicarbonate/sulfate/chloride water types which depict source water variability greater than that shown in the bedrock aquifers in Figure 7 yet significantly more homogeneous than the source water variability shown in the alluvial and terrace piper plot (Figure 6). Contrastingly, the Ogallala-NW aquifer exhibits primarily Calcium/Sodium-bicarbonate waters. Figure 9 displays the major ion data for the BOON, RBDX and mixed BOON/RBDX* waters. The BOON water type is calcium-bicarbonate; the RBDX reflects a mix of water types because groundwater transitions from calcium-bicarbonate to calcium/sodium-bicarbonate/chloride/sulfate from east to west within the aquifer. The water types of the BOON/RBDX sites are a mix of water quality types describing instances where the water from the BOON aquifer is more influential and in other instances the water quality of the RBDX is more predominant.

*mixed BOON/RBDX is designated as such due to these wells being drilled through both aquifers and being left open-hole through both, resulting in a mix of the aquifers' waters

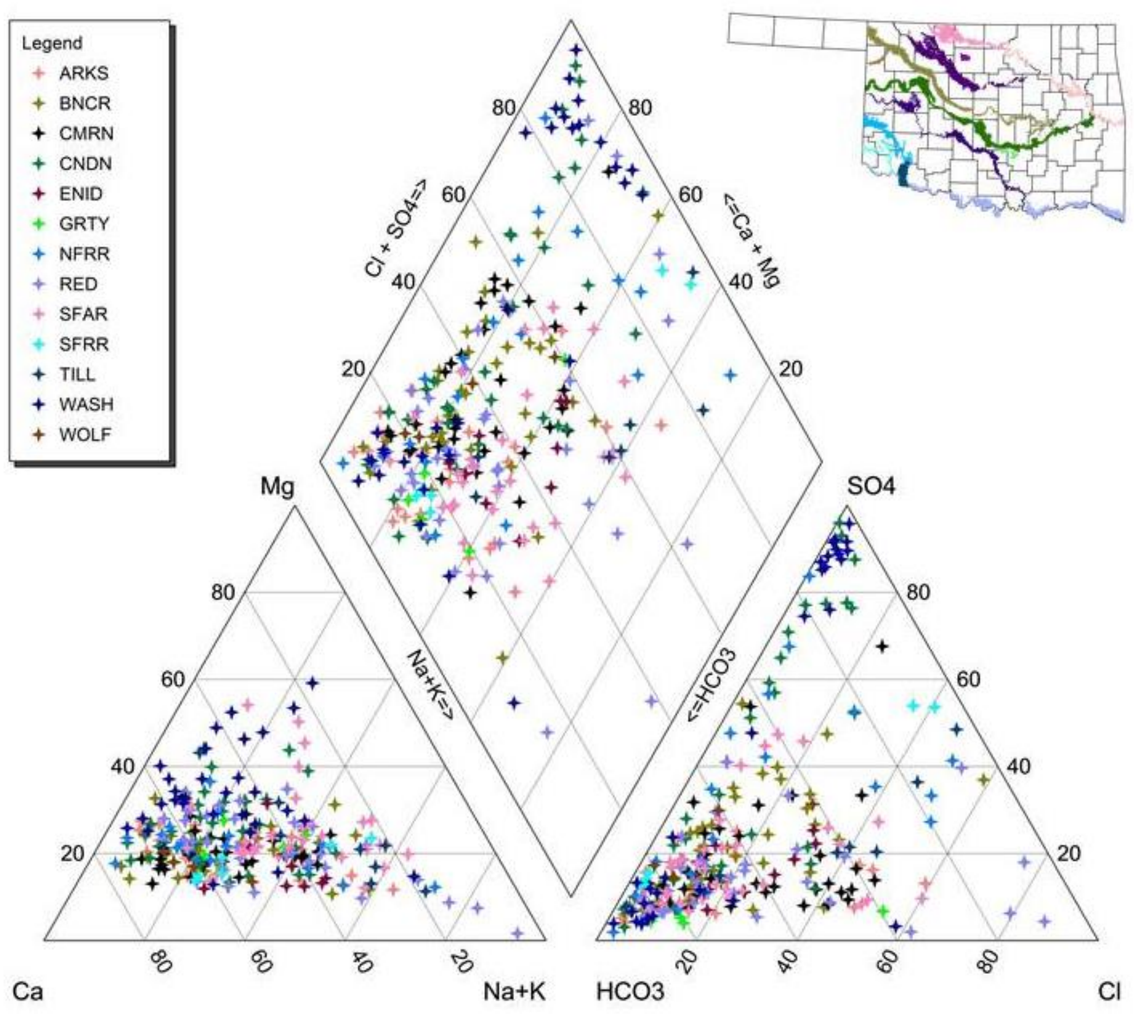


Figure 6. Piper plot diagram of constituents of alluvium and terrace aquifers sampled for the GMAP.

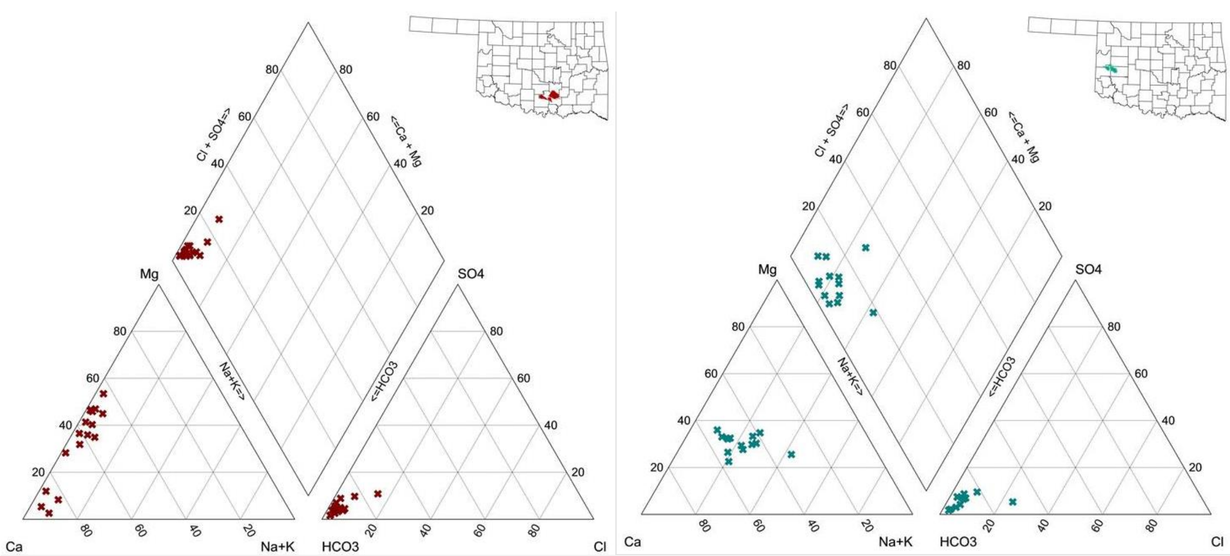


Figure 7. Piper plot diagrams of constituents of the ABSMP (left) and ELKC (right).

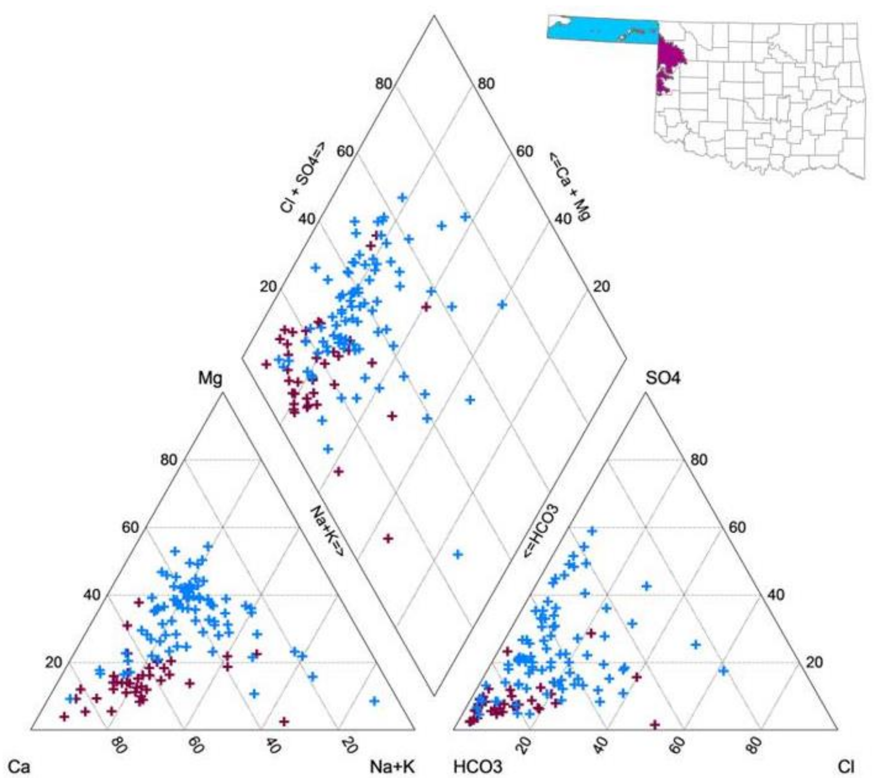


Figure 8. Piper plot diagram of constituents of the OGLLNW (red) and OGLLP (blue).

Parameters of Concern in Oklahoma

While there are few numerical beneficial use criteria developed for groundwater in the State of Oklahoma, all aquifers included in this study are used as drinking water sources for municipalities and/or private landowners. Therefore, water quality concerns can be summarized according to EPA's criteria for safe drinking water (Table 3). The most common water quality health concerns found across the state were nitrate and manganese (Table 5). The most common aesthetic concerns were chloride, iron, manganese, pH, sulfate, and total dissolved solids. However, hardness was observed at elevated levels for drinking water in 21 aquifers statewide (mean hardness >180 mg/L). The occurrence of some of these parameters is described in more detail below.

Table 5. Frequency of exceedances for parameters sampled for the GMAP.

Parameter	Exceedance Type	% samples exceeded	# aquifers exceeded
Arsenic	MCL	1.9	6
Fluoride	MCL	1.0	2
Lead	MCL	0.1	1
Manganese	Health Advisory	5.8	10
Molybdenum	Health Advisory	0.3	2
Nitrate	MCL	14.2	17
Radium (combined 226+228)*	MCL	n/a*	1*
Selenium	MCL	0.1	1
Uranium	MCL	0.8	5
Aluminum	SMCL	0.1	1
Chloride	SMCL	4.0	15
Fluoride	SMCL	4.0	6
Iron	SMCL	8.0	14
Manganese	SMCL	12.3	14
pH	SMCL	11.4	16
Sulfate	SMCL	11.0	12
Total dissolved solids	SMCL	32.3	22
TOTAL		725 samples	24 aquifers

*Only tested for in one aquifer

Table 6. Aquifers with the fewest number of exceedances relative to number of samples collected.

Aquifer	Number of exceedances	Total analyses performed	% exceedance
ELKC	0	208	0.0
ABSMP	2	288	0.7
BOON	4	544	0.7
WOLF	1	64	1.6
OGLL	45	2048	2.2
GSWF	27	752	3.6

Total Dissolved Solids Discussion

Total Dissolved Solids (TDS) is a term used to describe the total of inorganic salts and small organic matter concentrations in water. TDS content in a water sample is often used as a general indicator of water quality. Although the OWRB considers water with a dissolved solid concentration of less than 5,000 mg/L (milligrams per liter) to be fresh, water is usually considered undesirable for drinking if the quantity of dissolved minerals exceeds 500 mg/L and constitutes the EPA's SMCL. The primary ions in groundwater that compose or account for TDS are calcium, potassium, magnesium, sodium, chloride, sulfate, and bicarbonate. The concentrations of these ions provide the basis for describing the general characteristics of the water and can provide insight into its origin. High TDS concentrations are often linked to non-health related impairments such as taste and odor.

As a regulatory matter; fresh water in Oklahoma includes all groundwater with TDS concentration of less than 10,000 mg/L. TDS is also used to classify groundwater as to their beneficial use. Groundwaters with TDS concentrations of less than 3,000 mg/L are considered to meet the beneficial use criteria for public and domestic drinking water, industrial and agriculture. Most of Oklahoma's major aquifers have TDS content much lower than this threshold.

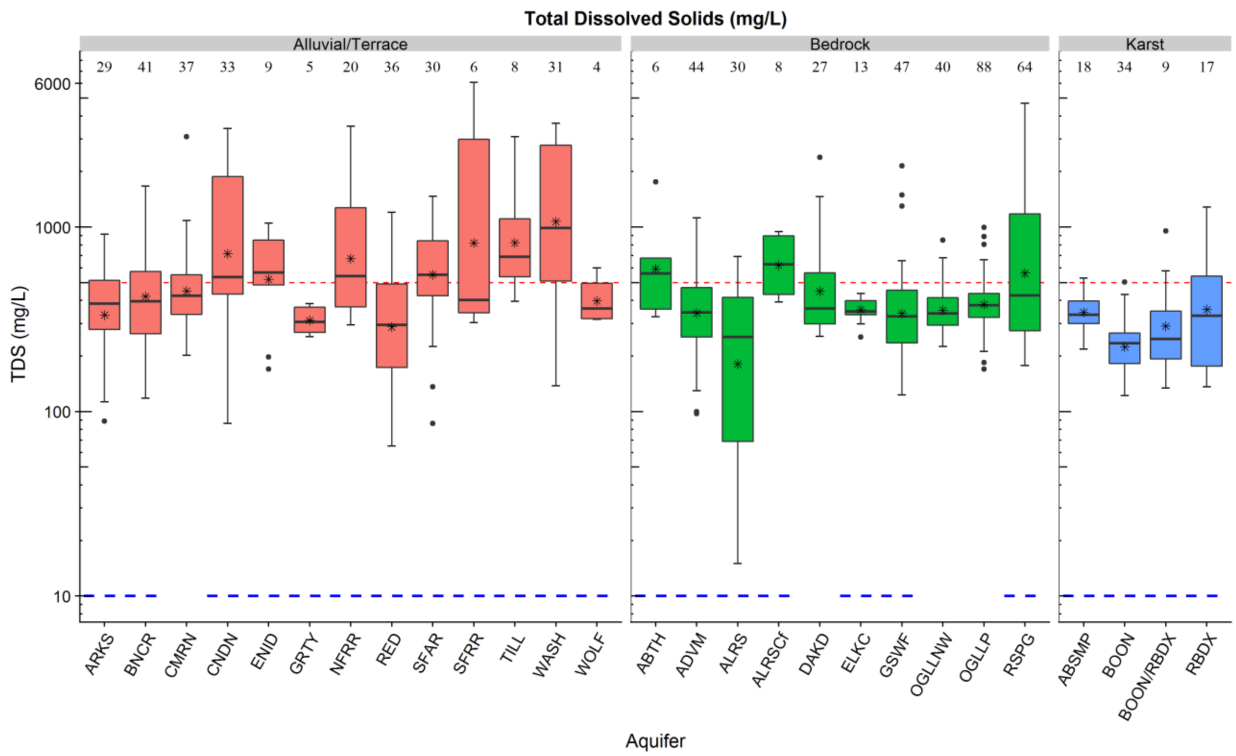


Figure 9. Boxplots of TDS concentrations (mg/L) by aquifer.

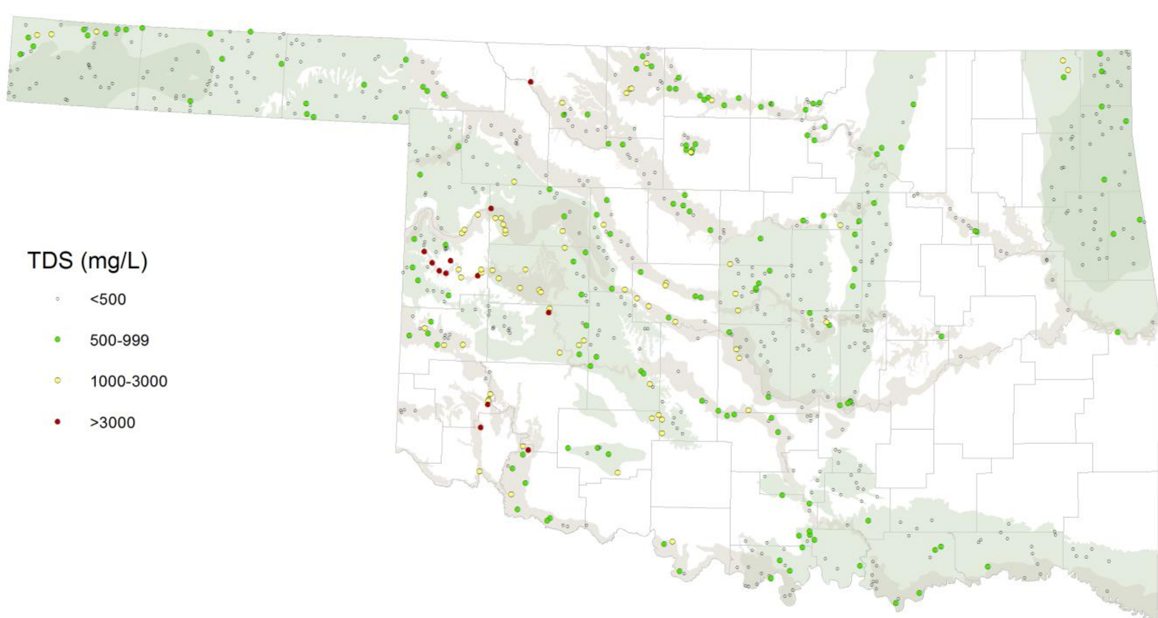


Figure 10. TDS concentrations (mg/L) in aquifers across the state.

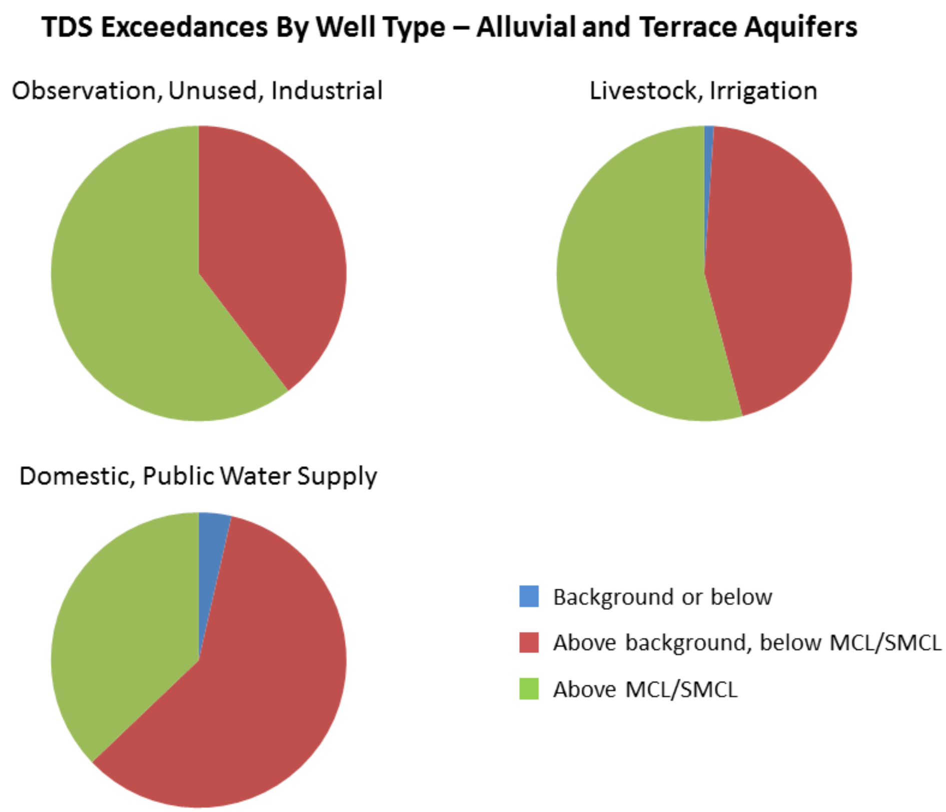


Figure 11. TDS concentrations (mg/L) by well type for alluvial and terrace aquifers.

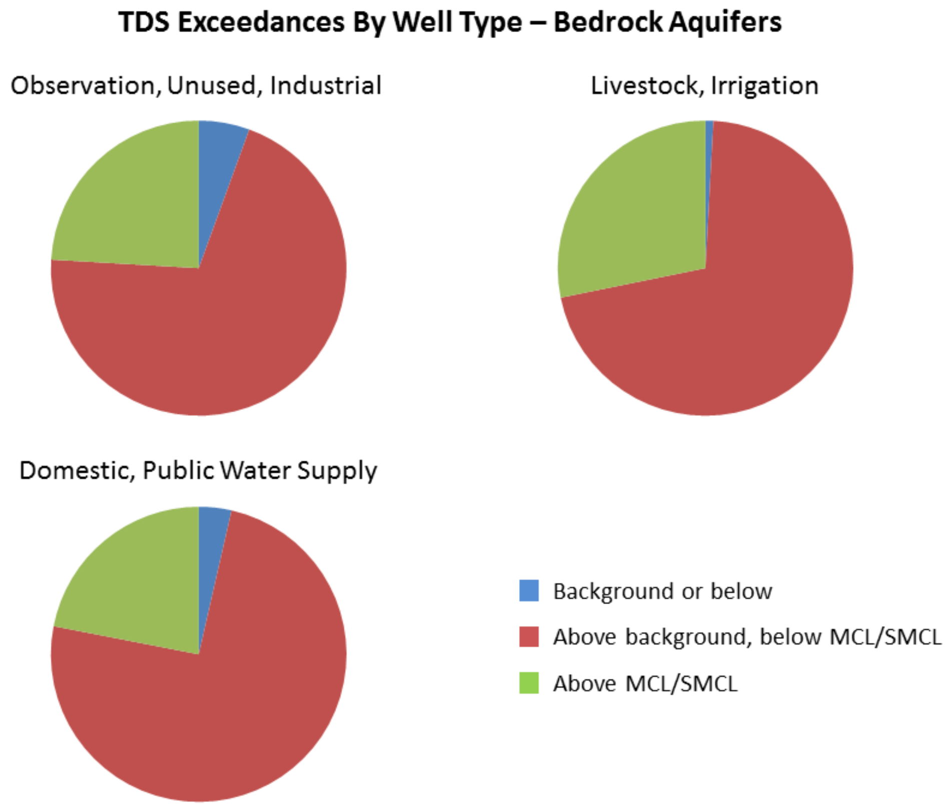


Figure 12. TDS concentrations (mg/L) by well type for bedrock aquifers.

Chloride/Sulfate Discussion

Natural sources of chloride in Oklahoma's aquifers can be derived from atmospheric deposition, sea brines, weathering of bedrock and soils and bedded or nodular deposits of halite in geologic formations (especially within the Permian formations of western Oklahoma). Man-made sources of chloride include wastes from septic-sewage systems, waste water retention lagoons, salt used for road de-icing and the production of chlorine and sodium hydroxide products. Chloride combines with various cations (such as sodium, calcium and magnesium) to form compounds of salt. The secondary maximum contaminant level (SMCL) threshold for chloride in drinking water is 250 mg/L (EPA). Water with concentrations at or near this threshold can give off a salty taste. At elevated levels, the consumption of water can elevate blood pressure and affect heart health, be corrosive to plumbing, water tanks and appliances and harm vegetation. The data from the GMAP baseline program indicate that chloride is not significant problem affecting Oklahoma's major aquifers in part because most wells are completed at depths significantly above the base of treatable water (TDS < 10,000 mg/L) or shallower than depths where natural brine water occurs. Over ½ of the samples tested had chloride concentrations of less than 20 mg/L and nearly 80% of the samples were less than 50 mg/L. Only 4% of 734 samples tested above the SMCL.

Natural sources of sulfate are derived from gypsum and anhydrite compounds and are most prevalent in western Oklahoma's Permian bedrock formations. Man-made sources include the deposition of sulfur from the combustion of fossil fuels. Subsequent oxidation of the sulfur and deposition through precipitation provide a mechanism for introduction into an aquifer. The SMCL for sulfate is 250 mg/L; at higher concentrations, sulfate laden water if consumed can create a laxative affect. An important aquifer (Blaine) in southwestern Oklahoma used primarily for crop irrigation is composed of interbedded shale, gypsum and dolomite. The concentrations of sulfate and TDS from this aquifer make it unsuitable as a drinking water supply. Overall, the baseline data reflect a regional pattern to where sulfate affects groundwater quality in Oklahoma. Seventy-nine of the 82 samples that exceeded the sulfate MCL and were located west of I-35; two-thirds of those samples were in western alluvial aquifers that immediately overlie or adjoin Permian formations where gypsum composes varying percentages of their matrix (Cloud Chief, Hennessey, El Reno Group).

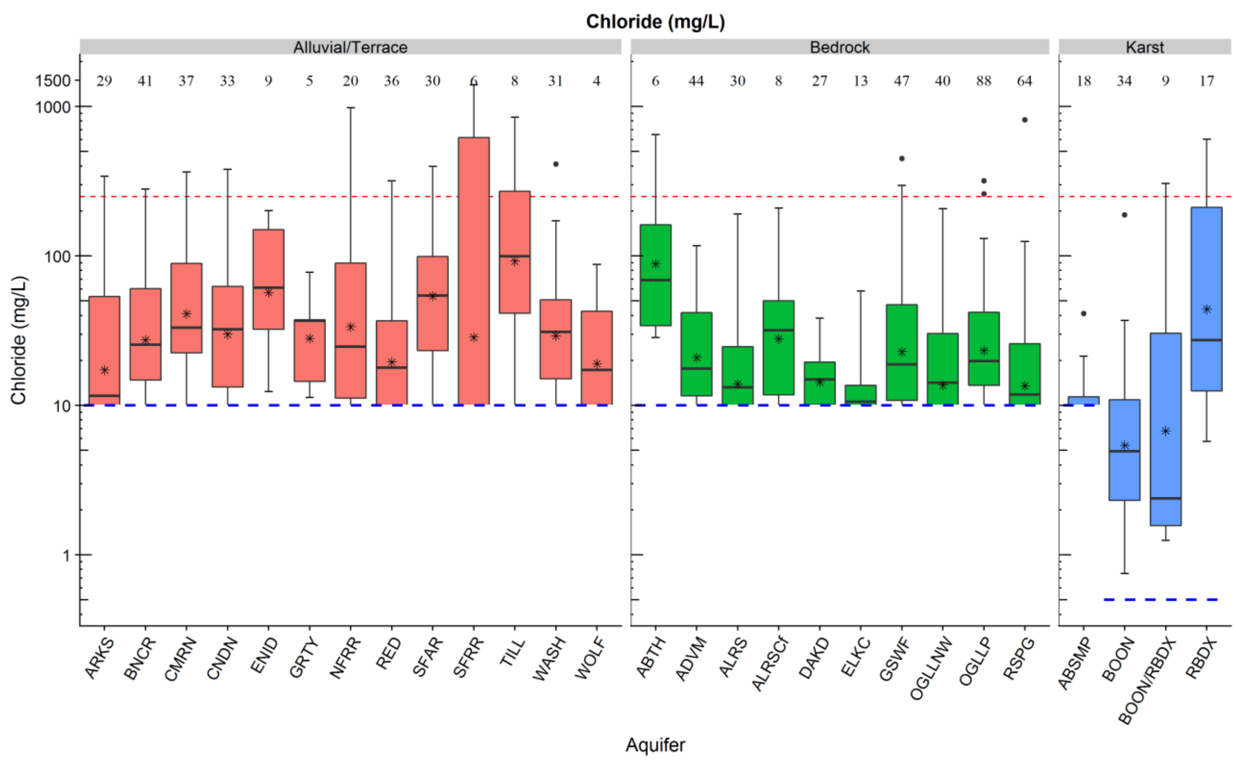


Figure 13. Chloride concentrations (mg/L) by aquifer.

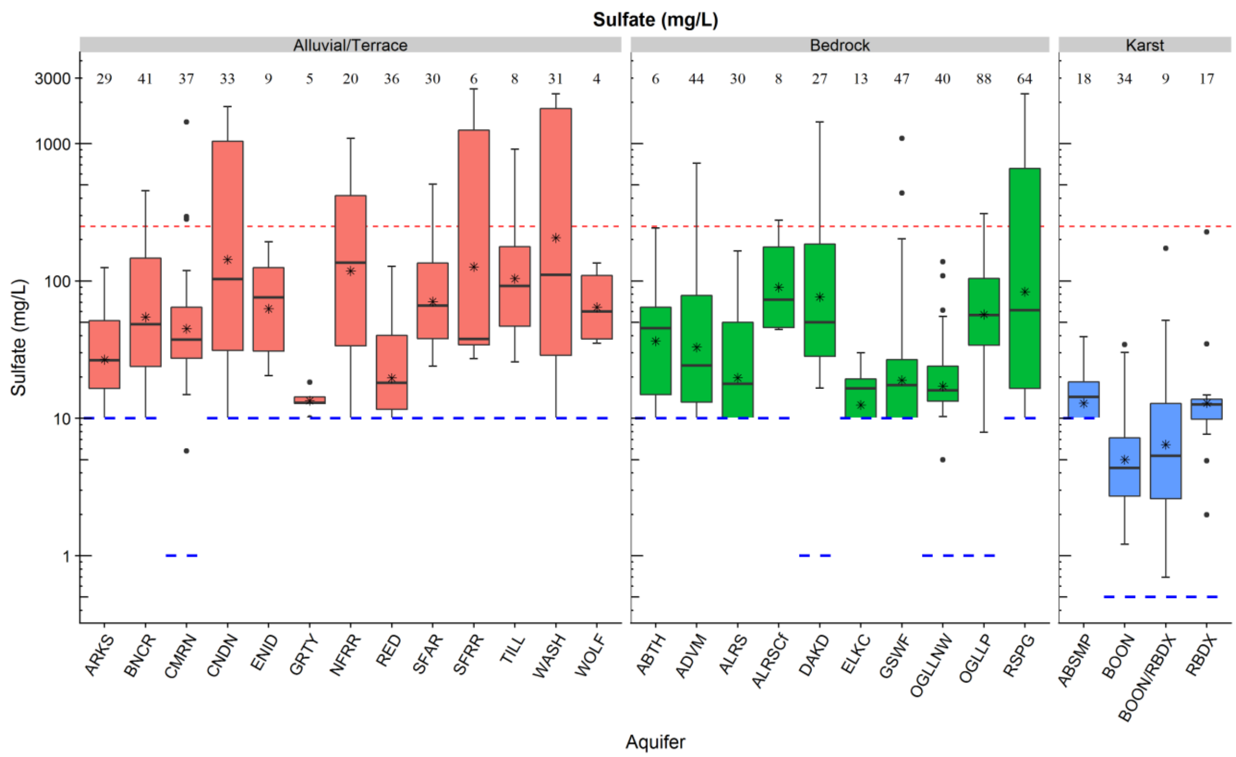


Figure 14. Sulfate concentrations (mg/L) by aquifer.

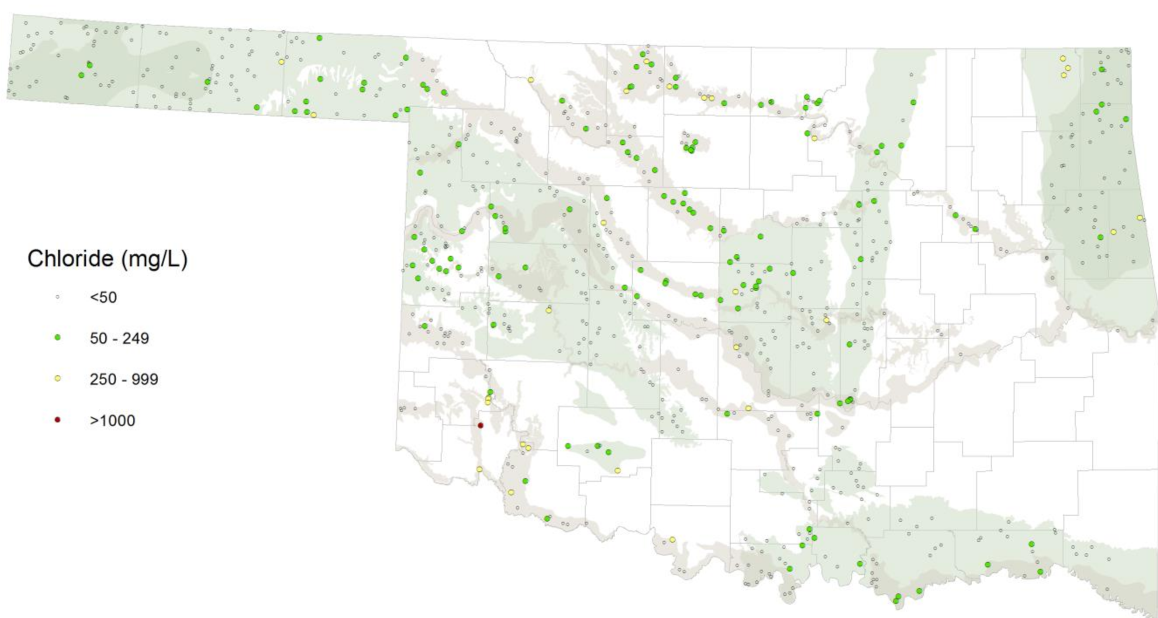


Figure 15. Chloride concentrations (mg/L) in aquifers across the state.

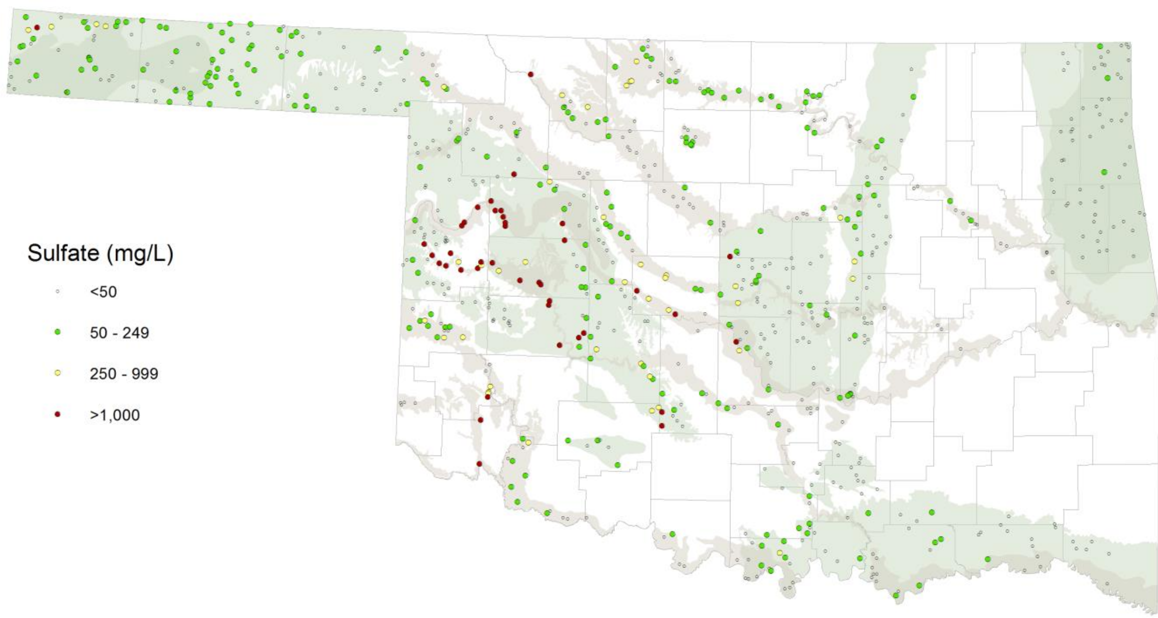


Figure 16. Sulfate concentrations (mg/L) in aquifers across the state.

Hardness Discussion

Degree of hardness in groundwater is mainly attributed to the presence of compounds containing calcium and magnesium. Hard water can lead to the formation of scale in water lines, pressure tanks and industrial boilers. It also requires additional soap for domestic washing/laundry etc. Water hardness is measured in mg/L of calcium carbonate. Median hardness in 21 of the 26 aquifers tested place Oklahoma's groundwater's in the hard (121-180 mg/L) to very hard category (> 180 mg /L). Only the ABTH and confined portions of the ALRS exhibited soft water conditions (< 61 mg/L). ("Water Hardness and Alkalinity," 2016)

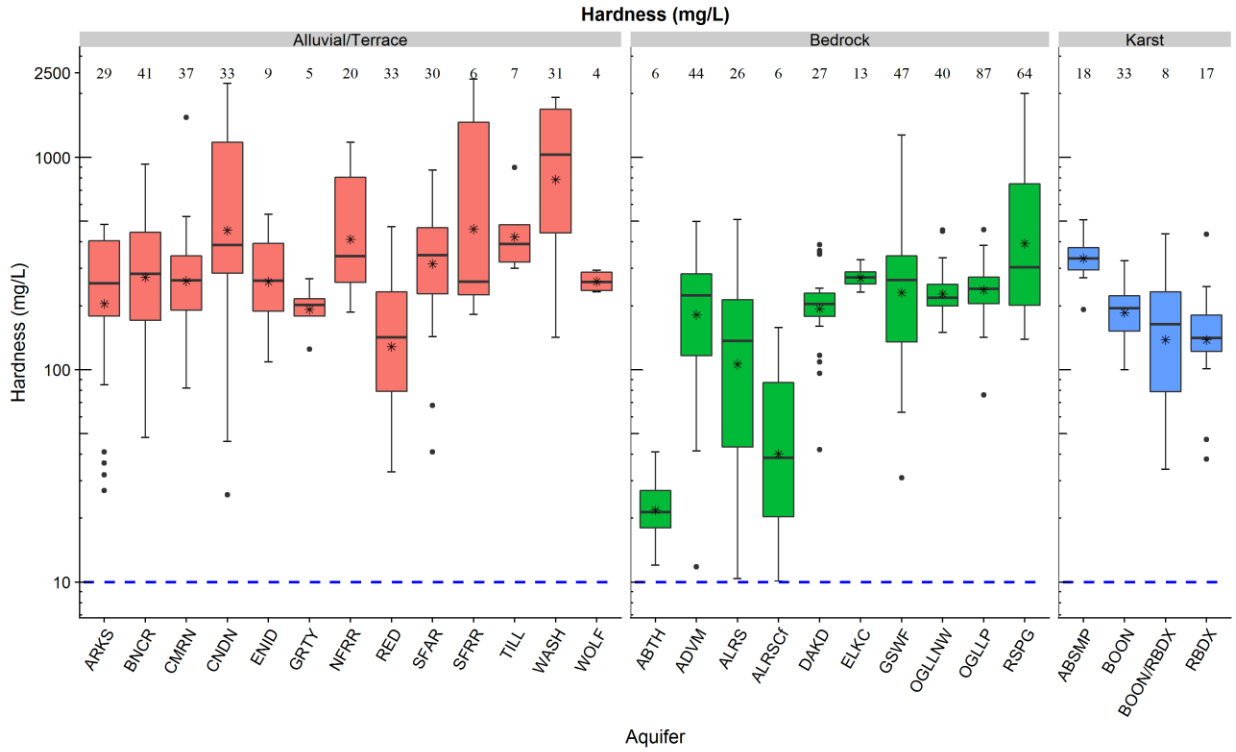


Figure 17. Hardness concentrations (mg/L) by aquifer.

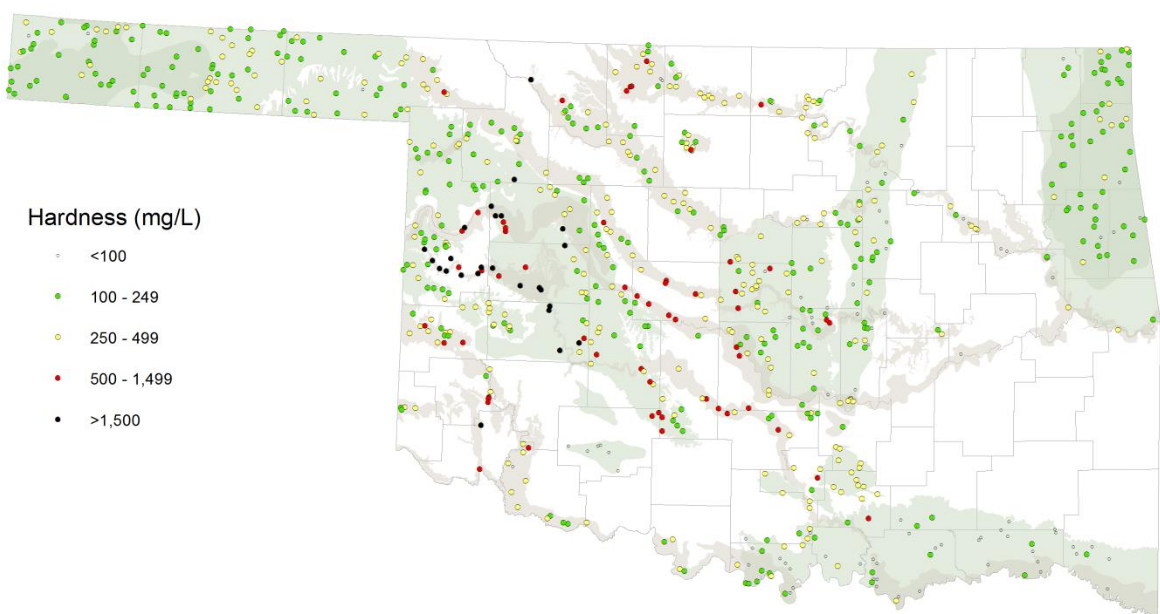


Figure 18. Hardness concentrations (mg/L) in aquifers across the state.

Iron and Manganese Discussion

Iron (Fe) and manganese (Mn) are trace elements that are essential for the development and growth of the skeletal structure. High concentrations of Fe and Mn can result in metallic tasting water, staining of clothes and the formation of precipitates (oxidation) in piping that can restrict water flow. Mn and Fe are present in most rock types and their presence in groundwater is controlled in large part by their water chemistry; specifically oxidation reduction potential (redox), dissolved oxygen (DO) content and microbiological activity. (Homoncik, Et. Al., 2010) Mn has a higher redox than Fe meaning that as the groundwater environment transforms from oxic to anoxic, Mn will appear before and more prevalent than Fe, however as the redox environment continues reduce, the prevalence of Fe compared to Mn should increase. (Ohio EPA, 2014) Most MCL exceedances for Mn and high levels of Fe (> 500 µg/L) occurred when redox and DO were low (ORP<200, DO <1 mg/L). However, this did not always hold true and may be explained by the source water being obtained from longer screened wells that included zones with mixed redox. Other controls cited in literature relating to the presence or absence of Mn and Fe include pH, well depth, and geology. 80% of sites where Mn exceeded the MCL were from alluvial and terrace aquifers. The five aquifers with the most frequent occurrences of Mn above its MCL were the ARKS, CNDN, BNCR, WASH and ALRS.

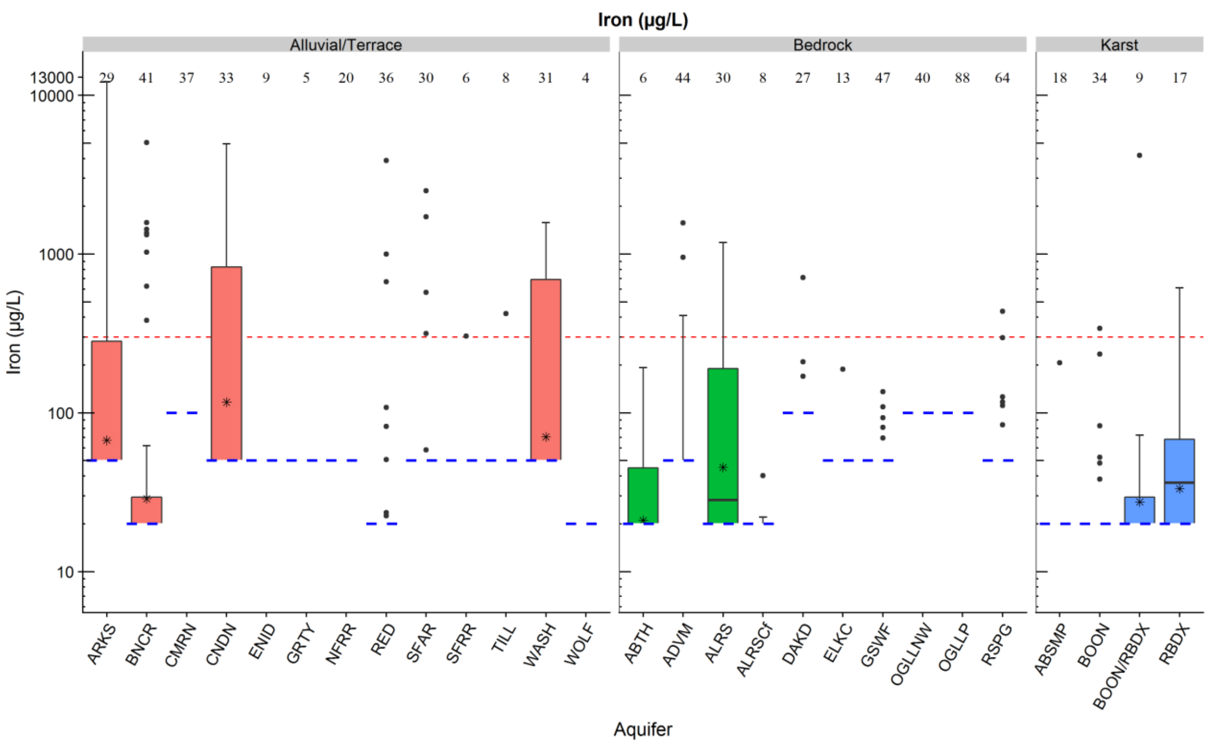


Figure 19. Iron concentrations (µg/L) by aquifer.

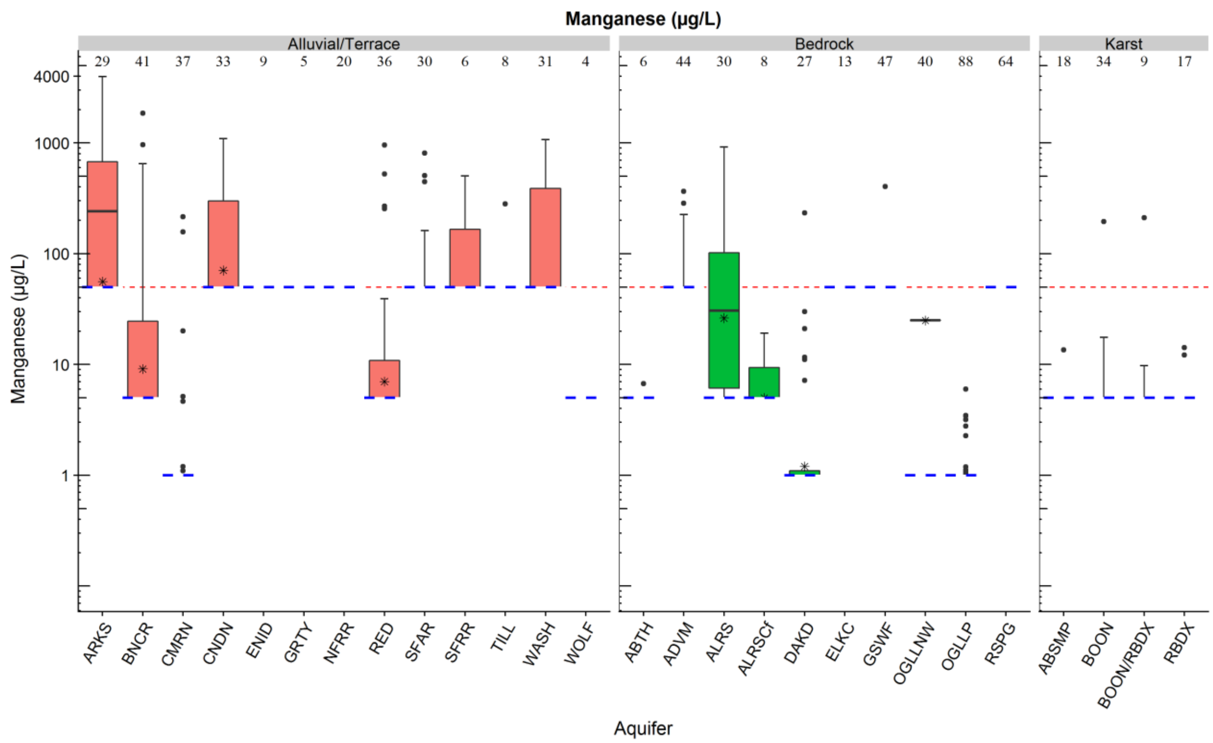


Figure 20. Manganese concentrations (µg/L) by aquifer.

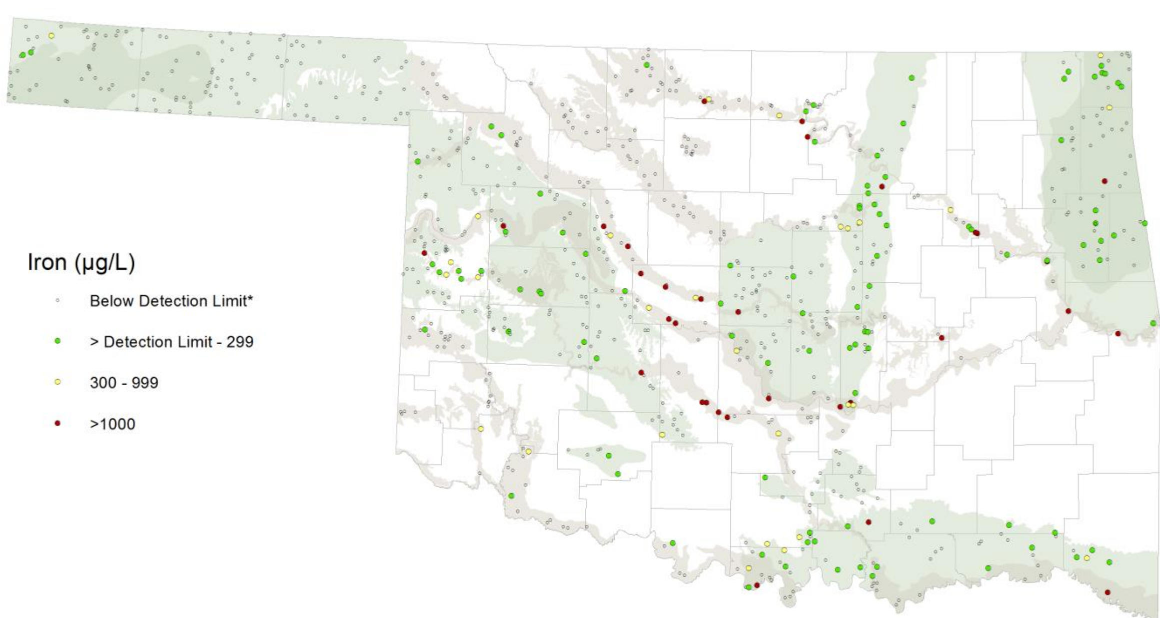


Figure 21. Iron concentrations (µg/L) in aquifers across the state (*Detection limits varied across years.)

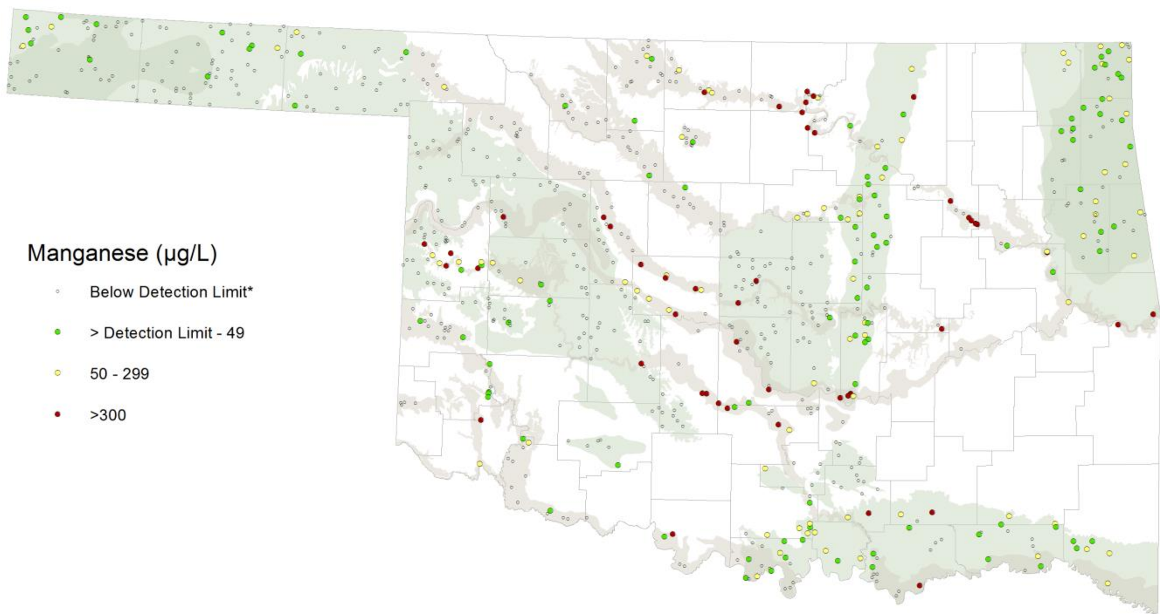


Figure 22. Manganese concentrations (µg/L) in aquifers across the state. (*Detection limits varied across years.)

Nitrate-N Discussion

Nitrate-N is a nutrient that is essential for plant and animal growth and nourishment. Naturally, air is composed of about 78% nitrogen gas; however man-made sources of nitrate-N include sewage and fertilizer. The occurrence of nitrate-N in groundwater can be from atmospheric deposition and from infiltration of nitrate-N compounds derived from waste water lagoons, septic system, and fertilizer. Nitrate-N levels in groundwater that exceed 2-3 mg/L indicate potential impacts from man-made activities. Nitrates are known to restrict the flow of oxygen in the bloodstream and is the most widely found contaminant in groundwater. (Freeze and Cherry, 1979) Nitrate-N is very mobile in groundwater and aquifers with sandy soils, shallow land surface slopes, thin unsaturated zones and shallow depths to water are very vulnerable to this constituent. Karst aquifers are also very susceptible to contaminants such as nitrates due to their ability to transmit surface contaminants directly to the water table through natural fractures. The box plots of the baseline nitrate-N data (Figure 24) reflect that Oklahoma's alluvial aquifers are showing the greatest stress in relation to nitrate. Variable land uses across the state and across an aquifer's extent may explain why not all alluvial and terrace aquifers exhibit the same levels of nitrate-N Results from the GMAP's baseline sampling showed that of wells exceeding the EPA MCL, 75% of those wells were found in alluvial and terrace aquifers. Of all alluvial and terrace aquifer wells sampled, 27% of those wells were found to be over the MCL. In contrast, only 5% of the exceedances occurred with Oklahoma's bedrock aquifers.

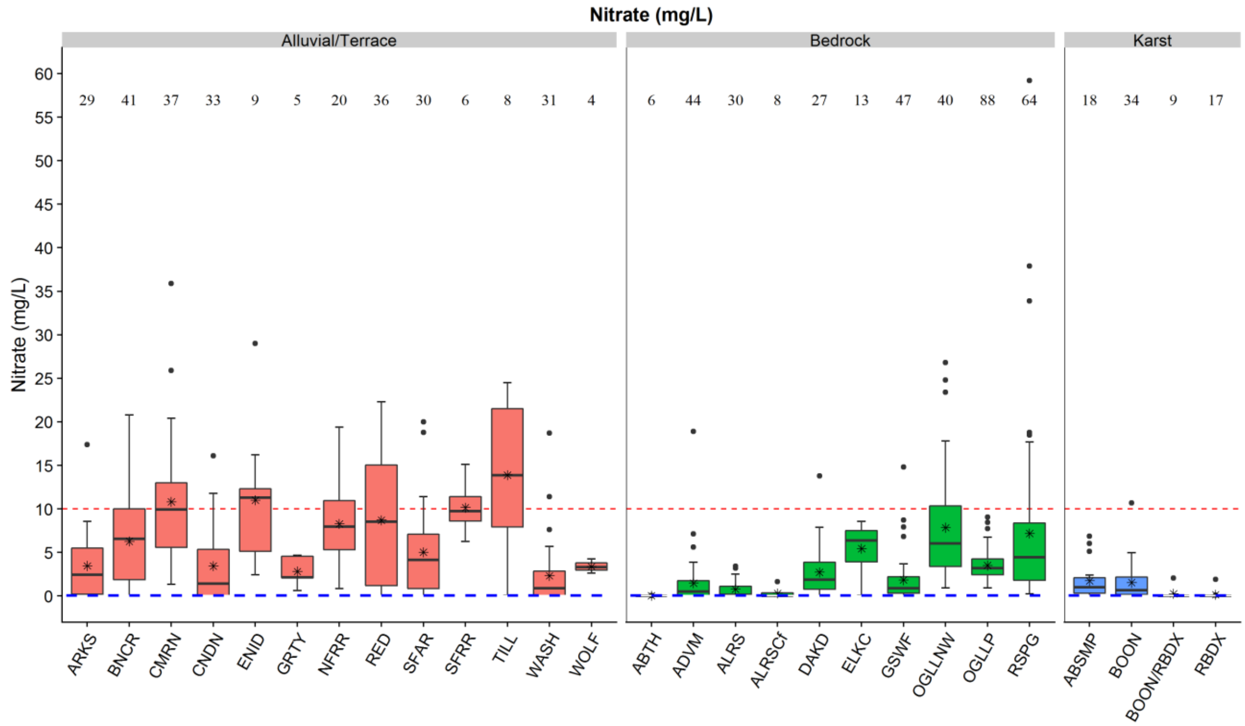


Figure 23. Nitrate concentrations (mg/L) by aquifer.

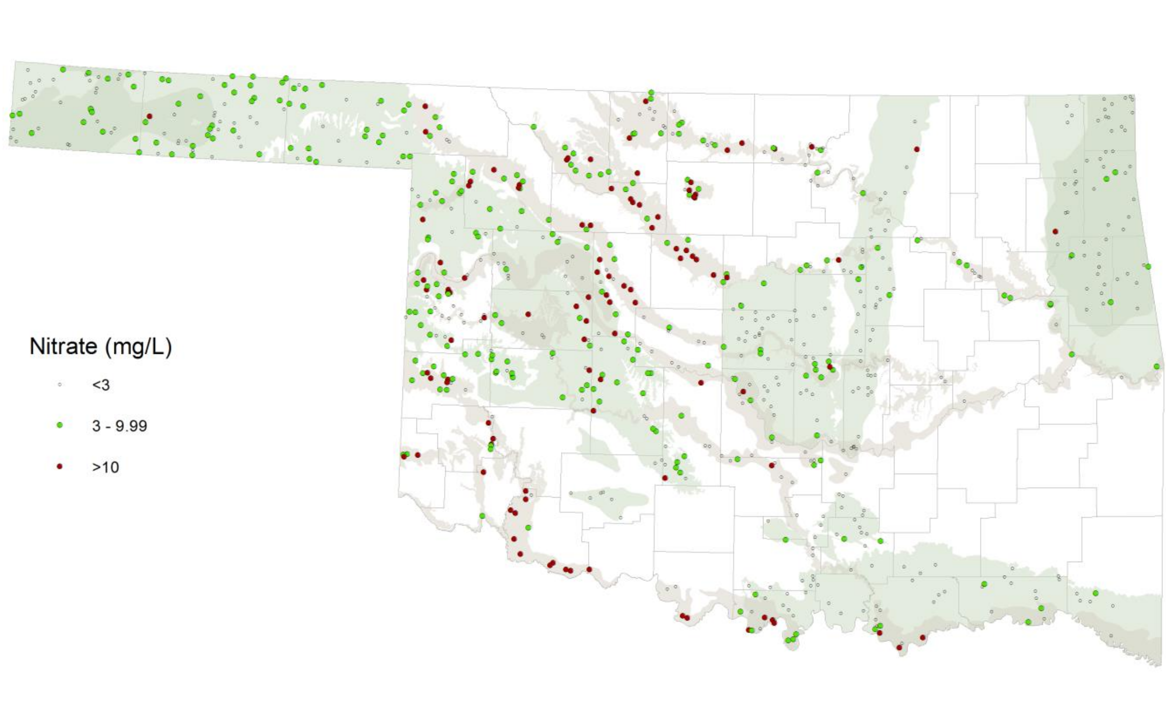


Figure 24. Nitrate concentrations (mg/L) in aquifers across the state.

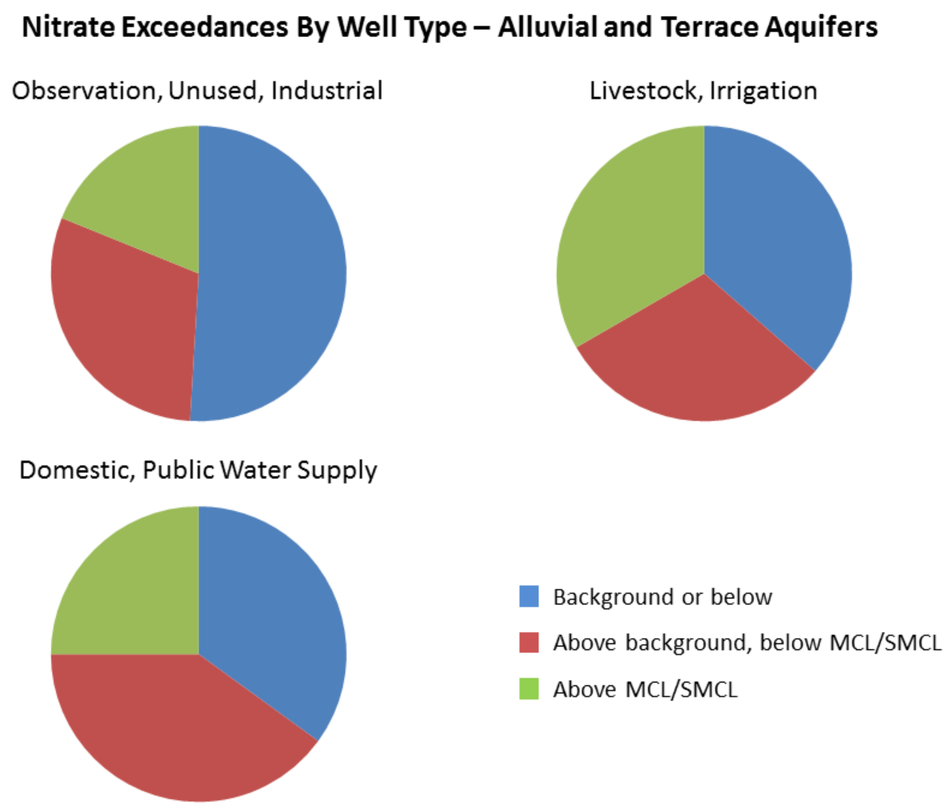


Figure 25. Nitrate concentrations (mg/L) by well type in alluvium and terrace aquifers.

Water Level Trend Network

Groundwater level measurements, determined manually with graduated tapes or with down-hole pressure transducers, can be shown using well hydrographs that plot the time series versus the depth to water or water level elevation. Well hydrographs may be representative of a localized area if few sites are available or may be representative of parts of or entire areas of aquifers if an extensive network is available. When characterizing groundwater levels related to ambient hydrologic and climate effects, ideal target sites are unused wells isolated from areas of large groundwater withdrawals. However, in order to obtain spatial representativeness within an aquifer, a network of sites provides groundwater level data from areas of the aquifer that are not influenced by groundwater withdrawals and reflect ambient conditions along with those that are impacted by withdrawals. Data from both types of sites are useful for interpreting groundwater level changes resulting from natural and/or anthropogenic stressors.

Statewide Water Level Changes

When discussing groundwater levels and their change over time within Oklahoma's aquifers, references to the Oklahoma Climatological Survey's Climate Divisions (OCS; Figure 27) may be made to illustrate potential differences in groundwater conditions based on these climatic differences. The climate divisions represent geographical areas within the state that have similar meteorological characteristics like precipitation (rain/snow), temperature, barometric pressure, and wind velocity that may directly or indirectly influence groundwater availability and occurrence.

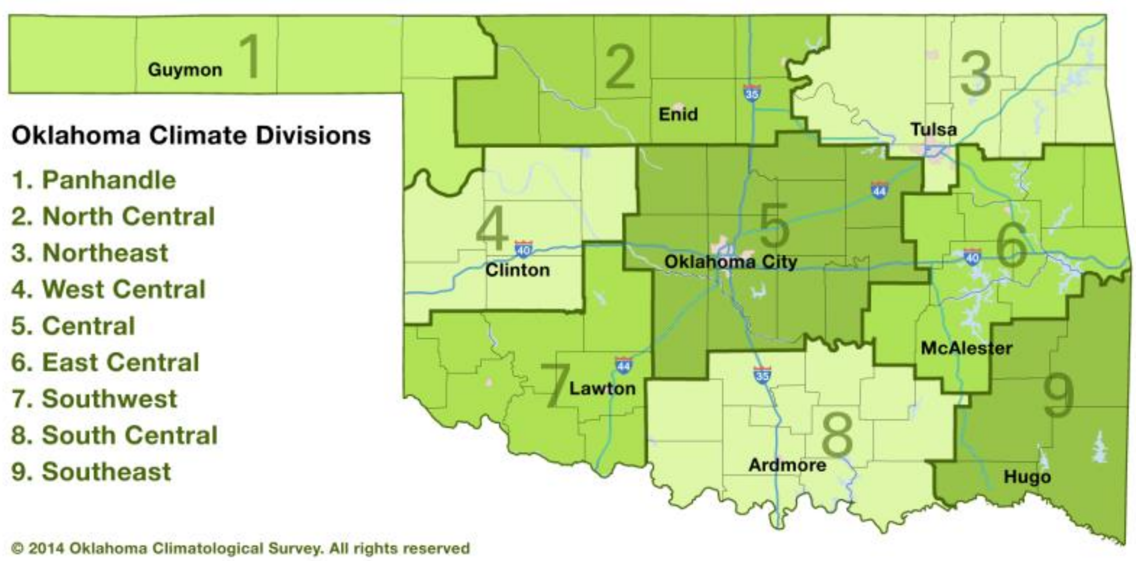


Figure 26. Oklahoma's climate divisions as mapped and provided by the OCS.

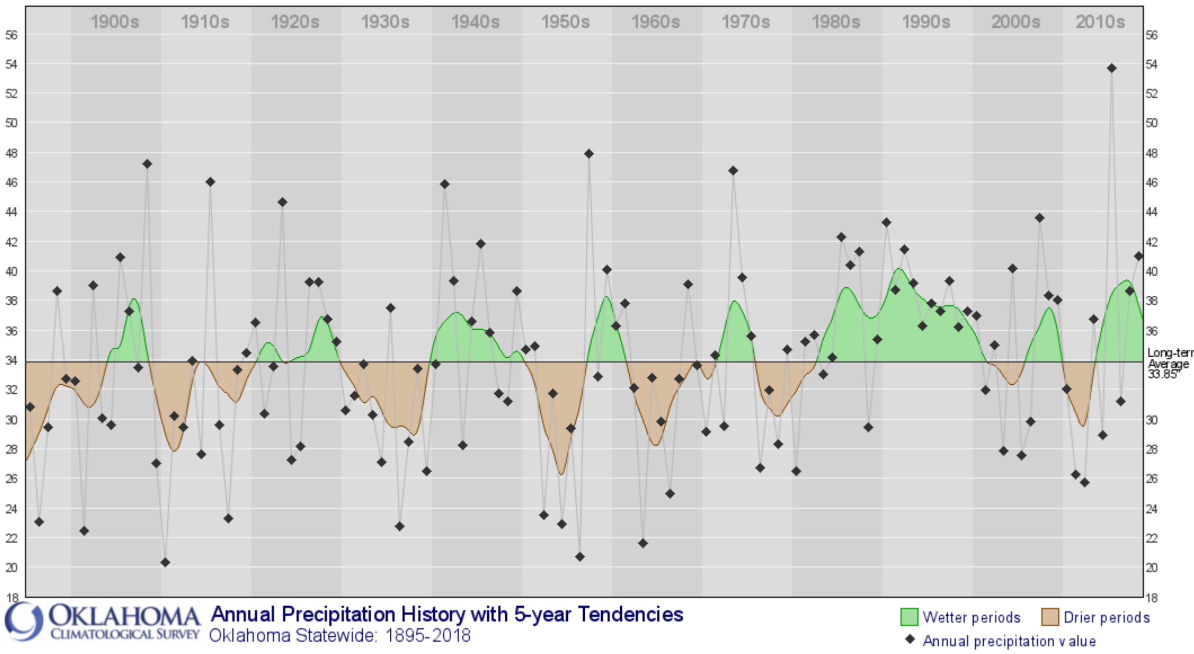


Figure 27. Statewide precipitation in Oklahoma over period of record (1895-2018) as presented and provided by the OCS.

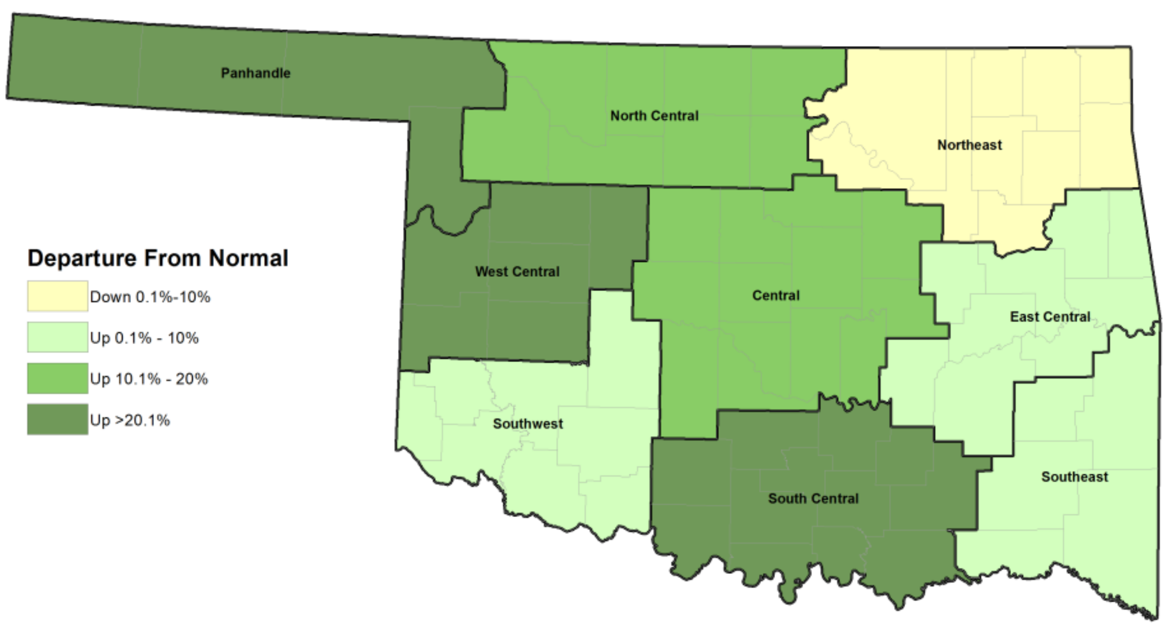


Figure 28. Precipitation for March 2018 to March 2019 compared to normal (1981-2010) values by climate division.

In 2018, statewide average precipitation was 7.65 inches above the 1981-2010 normal (Figure 28) marking the second consecutive year of overall wet conditions. Only the NE Climate Division recorded deficit precipitation in 2018 of 9% below normal. Average precipitation across the remaining 8 climate division ranged from slightly above normal to more than 20% above normal; the latter category included the Panhandle, West-central and South-central climate divisions (Figure 29). Figures 30-32 depict the 1, 5 and 10 year changes to average water levels in each aquifer in which there was sufficient monitoring sites for the specified time interval.

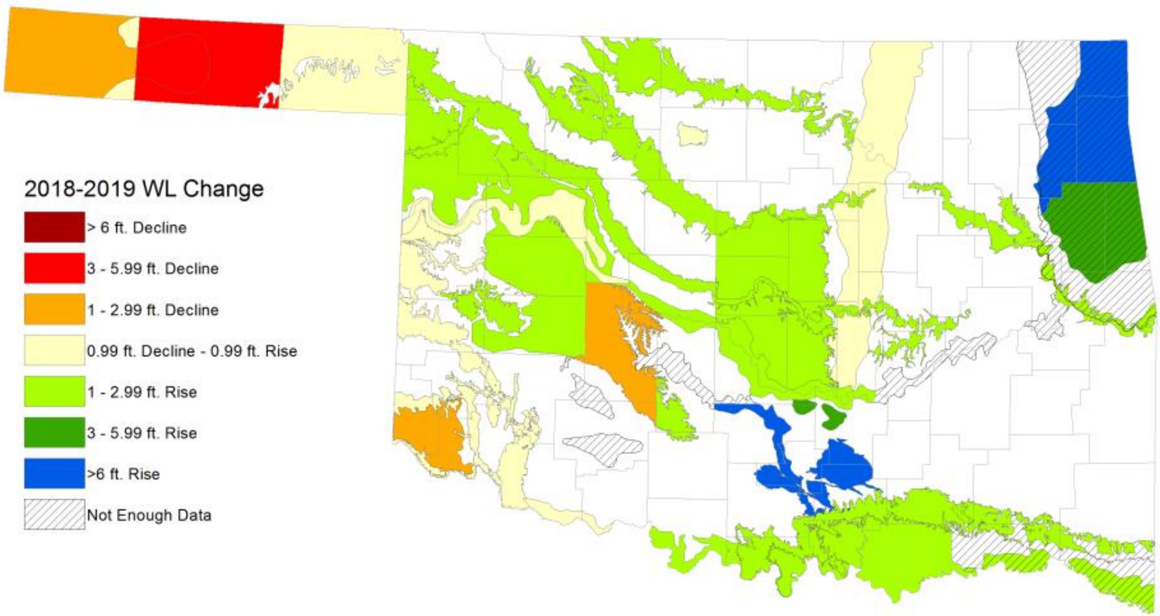


Figure 29. Average one year water level change by major aquifer and climate division (2018-2019).

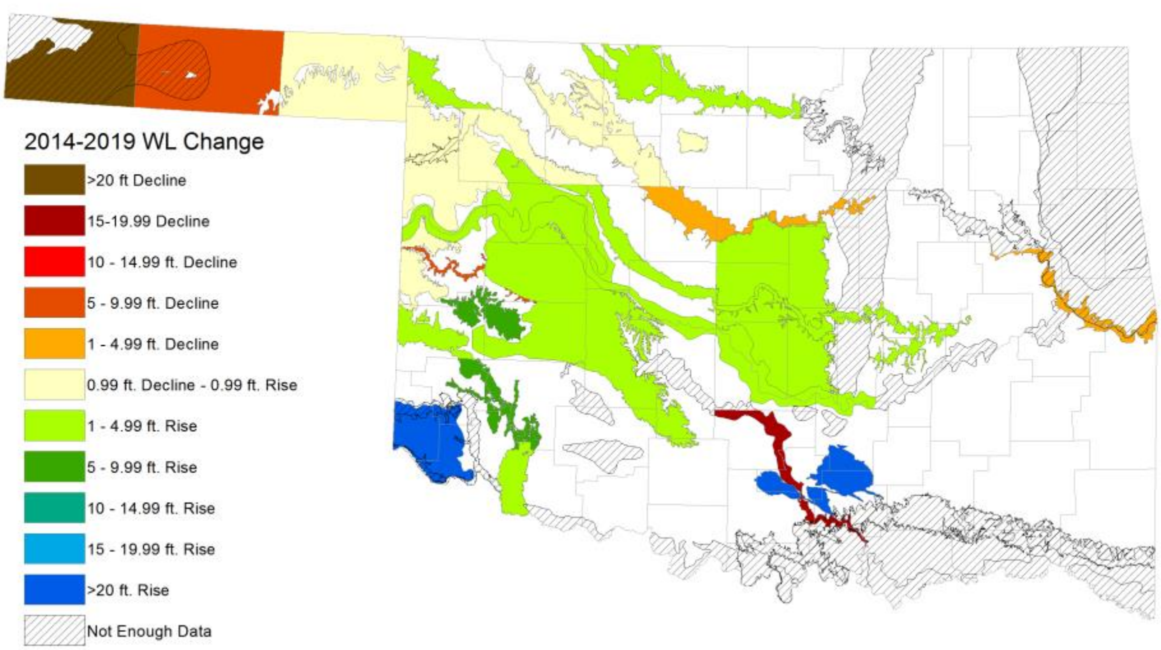


Figure 30. Average five year water level change by major aquifer and climate division (2014-2019).

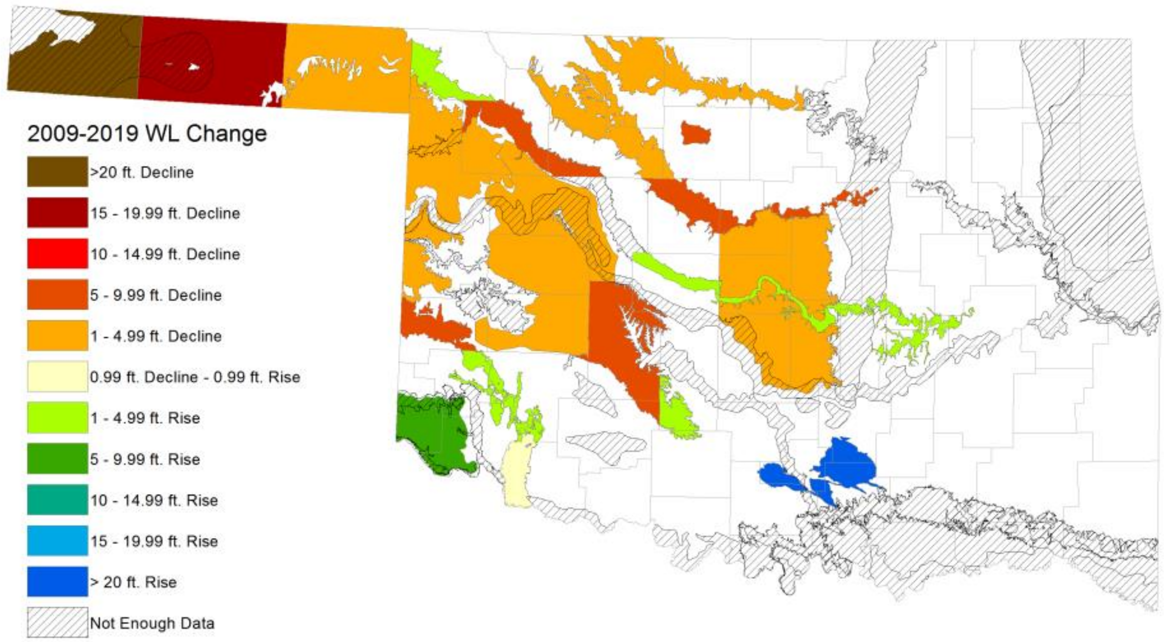


Figure 31. Average ten year water level change by major aquifer and climate division (2009-2019).

Statewide Water Level Changes

The water years of interest for evaluating the one, five and ten year change in water level maps are 2018, 2014 and 2009 respectively. Climatologically, 2018 and 2009 would be considered relatively wet, meaning that state wide precipitation for those three water years exceeded the long-term mean (1981-2010), and 2014 would be considered relatively dry. State-wide, Oklahoma received approximately 6 more inches of rain in 2018 compared to 2008 and approximately 4 more inches of precipitation in 2018 compared to 2013. Statewide, precipitation in 2018 was 7.65 inches above the historical mean. In general, if no artificial water withdrawals were occurring and precipitation was at or above normal, groundwater level rises would be the norm for these periods of record. However, regionally, in certain areas of the state large quantities of groundwater are pumped for crop irrigation and public water supply and significant drought occurred within the last decade. Also, the state-wide average precipitation does not take into account variation across the climate zones, i.e. does not capture regional or local variance in precipitation.

One Year Change in Groundwater Level Map (2018-2019)

Abundant rainfall in 2018 led to generally rising groundwater levels across the state. One to three foot increases were the norm along the Oklahoma-Texas border (ALRS and RED) as well as central, north central and northwestern regions (GSWF, SFAR, CMRN, BNCR, CANR and OGLLNW aquifers). Sharper increases ranging from 3 feet to more than 6 feet were reflected in the NE RBDX and BOON aquifers and south-central ABSMP aquifer. One to 3 foot declines were reflected in the SE part of the RSPG aquifer, the DCBG (SW) and Cimarron County of the OGLLP. Groundwater level decreases in the OGLLP aquifer in Texas County ranged from 3-6 feet (the steepest one year declines observed in the state). The remaining aquifers in Oklahoma generally held their own with groundwater level fluctuations ranging from +/-1 foot. The declining levels seen in the OGLLP, DCBG and RSPG are attributable to groundwater withdrawals for crop irrigation in spite of slight to moderate above normal precipitation in 2018.

Five Year Change in Groundwater Level Map (2014-2019)

The five year change map (2014-2019) reflects overall increasing water levels excepting the OGLLP aquifer in Texas & Cimarron Counties (due to groundwater withdrawals), lower WASH and eastern CMRN aquifers with maximum declines ranging from more than 15-20 feet, 5-10 feet and 1-5 feet respectively). Otherwise, with overall increasing precipitation in 2018 as compared to 2013 groundwater levels increased +/- 1 foot in the northwest, 1-5 feet in central and west central regions and more than 20 feet in the DCBG and ABSMP aquifers.

Ten Year Change in Groundwater Level Map (2009-2019)

The ten year groundwater level change map reflects declining water levels in most of the bedrock aquifers ranging from one to more than 20 feet for this period of record. Excepting the Panhandle area (whose declines are mainly attributable to groundwater withdrawals for crop irrigation), these declines are due to the intense climatological drought (Dec. 2009 – May 2015) that more than offset above normal precipitation received in 3 of the last 5 years that included the drought busting record rainfall during the last half of 2015. The effects of the drought can also still be observed in the western and central reaches of many of Oklahoma’s alluvial aquifers as well. Two of Oklahoma's karst aquifers (DCBG, ABSMP) show increases of five to twenty feet over the same period of record indicative of their inherent capability to be restored following a drought during above normal precipitation patterns.

Composite Hydrographs

Composite hydrographs provide an intuitive visual context for average water level in an aquifer over time. Wells are selected with the fewest number of data gaps possible to allow for a relatively uninterrupted composite average water level over a period of time. In order to avoid introducing bias from added or dropped wells, the same set of historical wells with contemporaneous measurements should be used for the entire period of record represented. The composite hydrographs that follow, grouped by aquifer type and climate division, represent the most complete picture of average water level possible with the available historical data.

Karst Aquifers

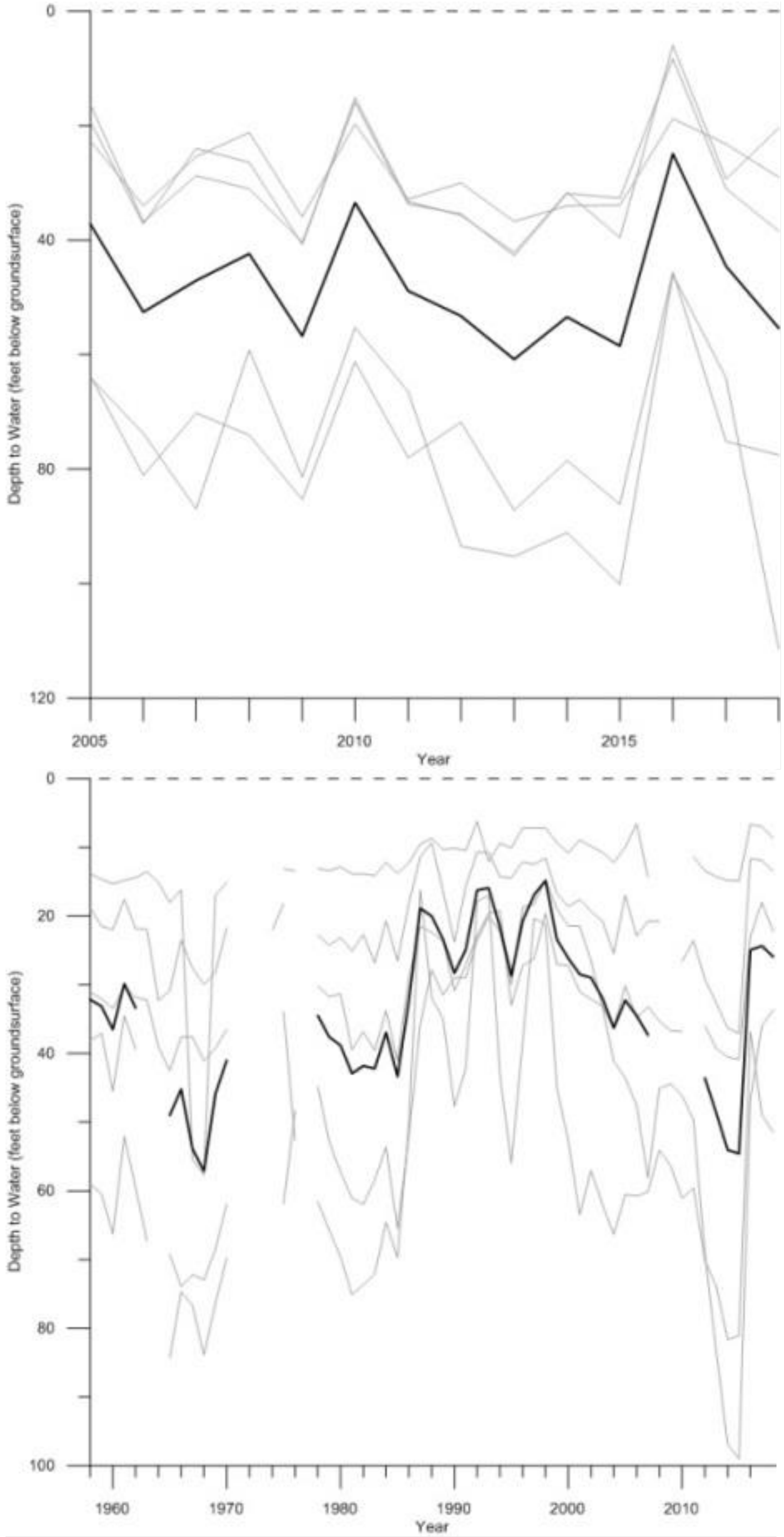
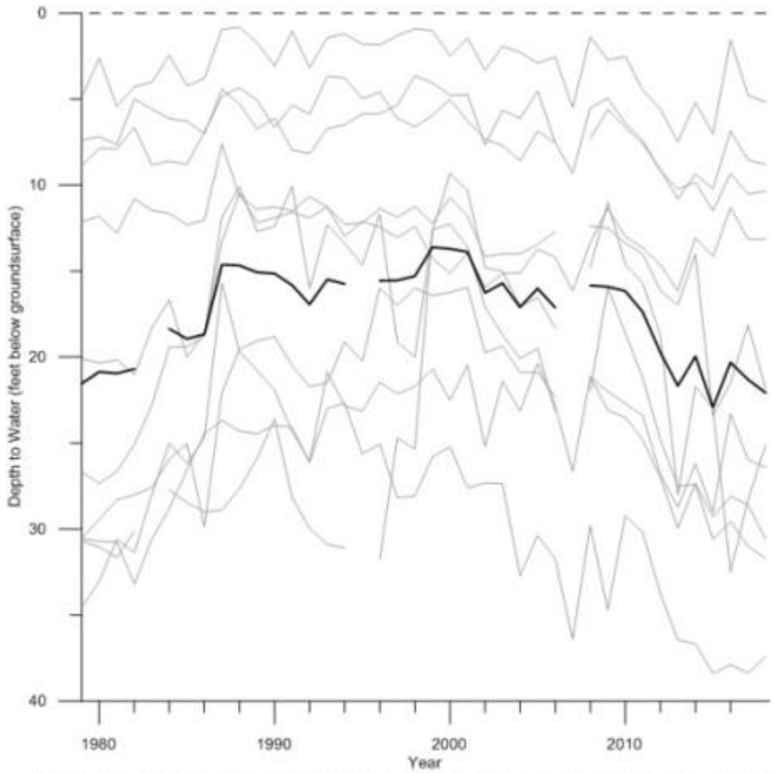


Figure 32. ABSMP (top; N=5; 2005-2018) and DCBG (bottom; N=5; 1958-2018).

Alluvial & Terrace Aquifers: Panhandle Climate Division



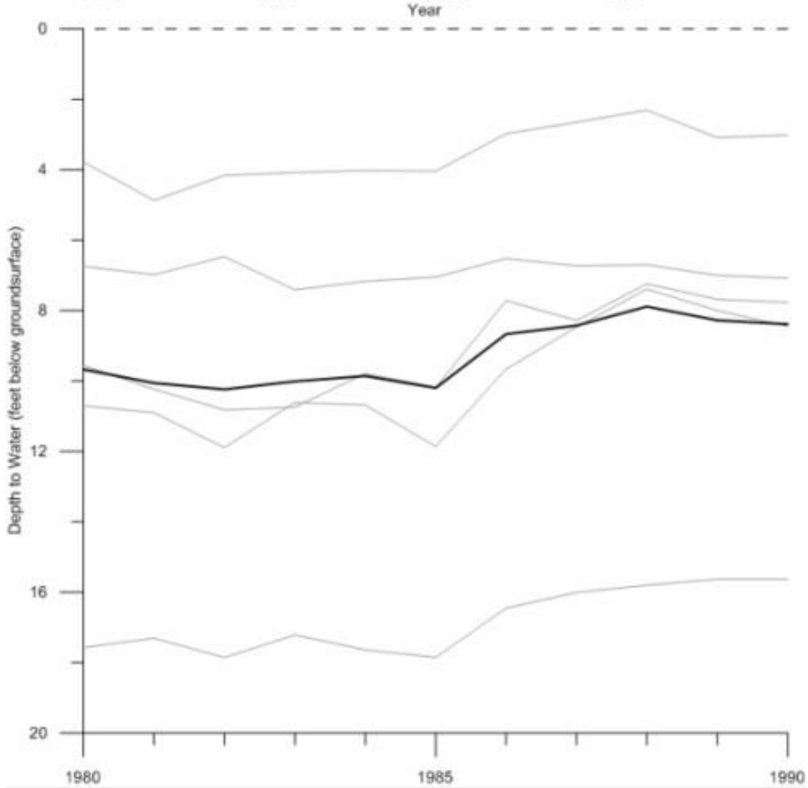
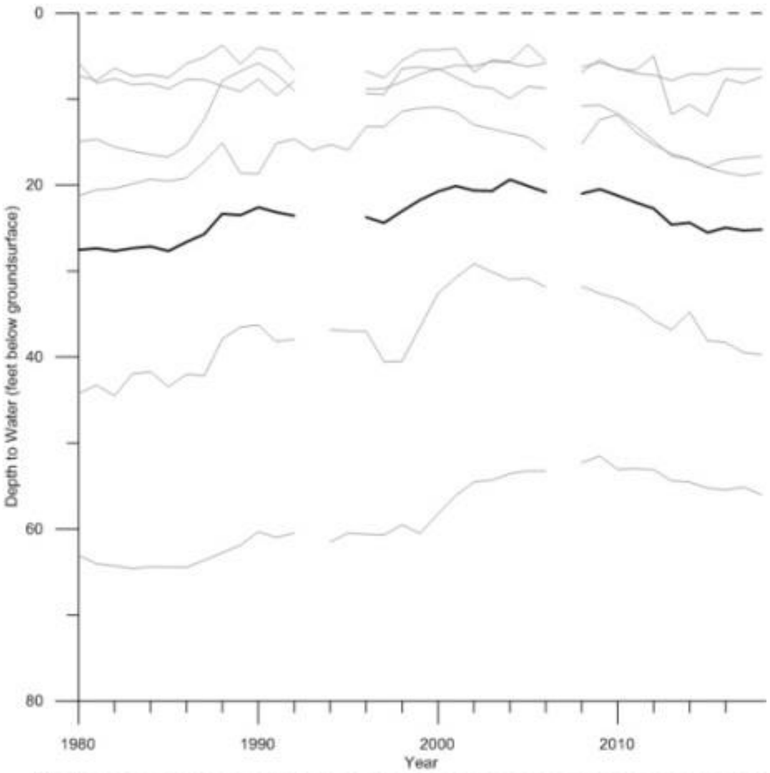


Figure 33. CMRN (N=8; 1979-2018; top) and WOLF minor (N=5; 1980-1990; bottom).

Alluvial & Terrace Aquifers: Multiple Climate Divisions



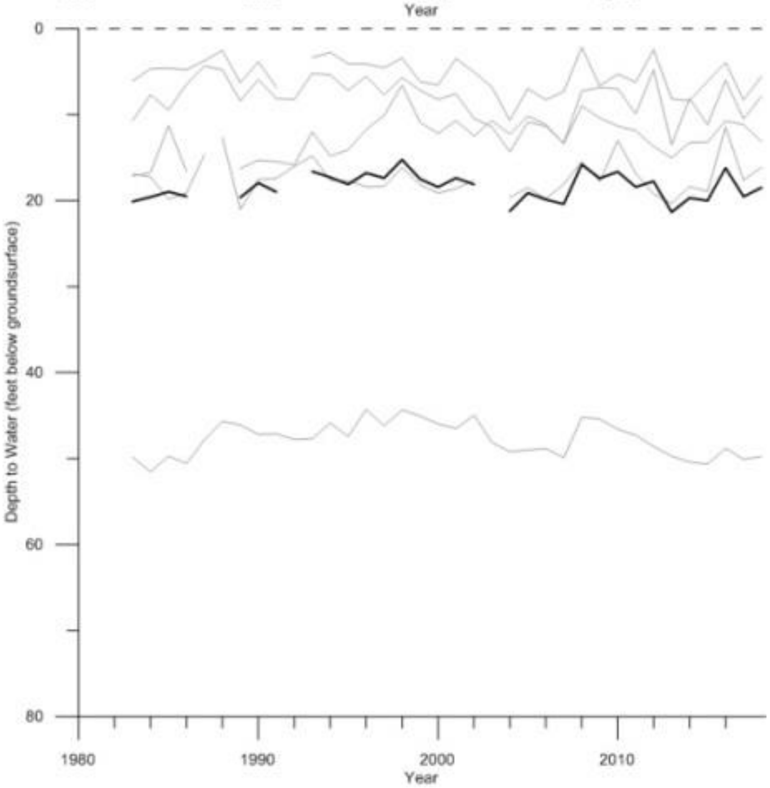


Figure 34. BNCR-Panhandle and North Central Climate Divisions (N=7; 1980-2018; bottom) and West Central and Central Climate Divisions (N=5; 1983-2018; bottom).

Alluvial & Terrace Aquifers: North Central Climate Division

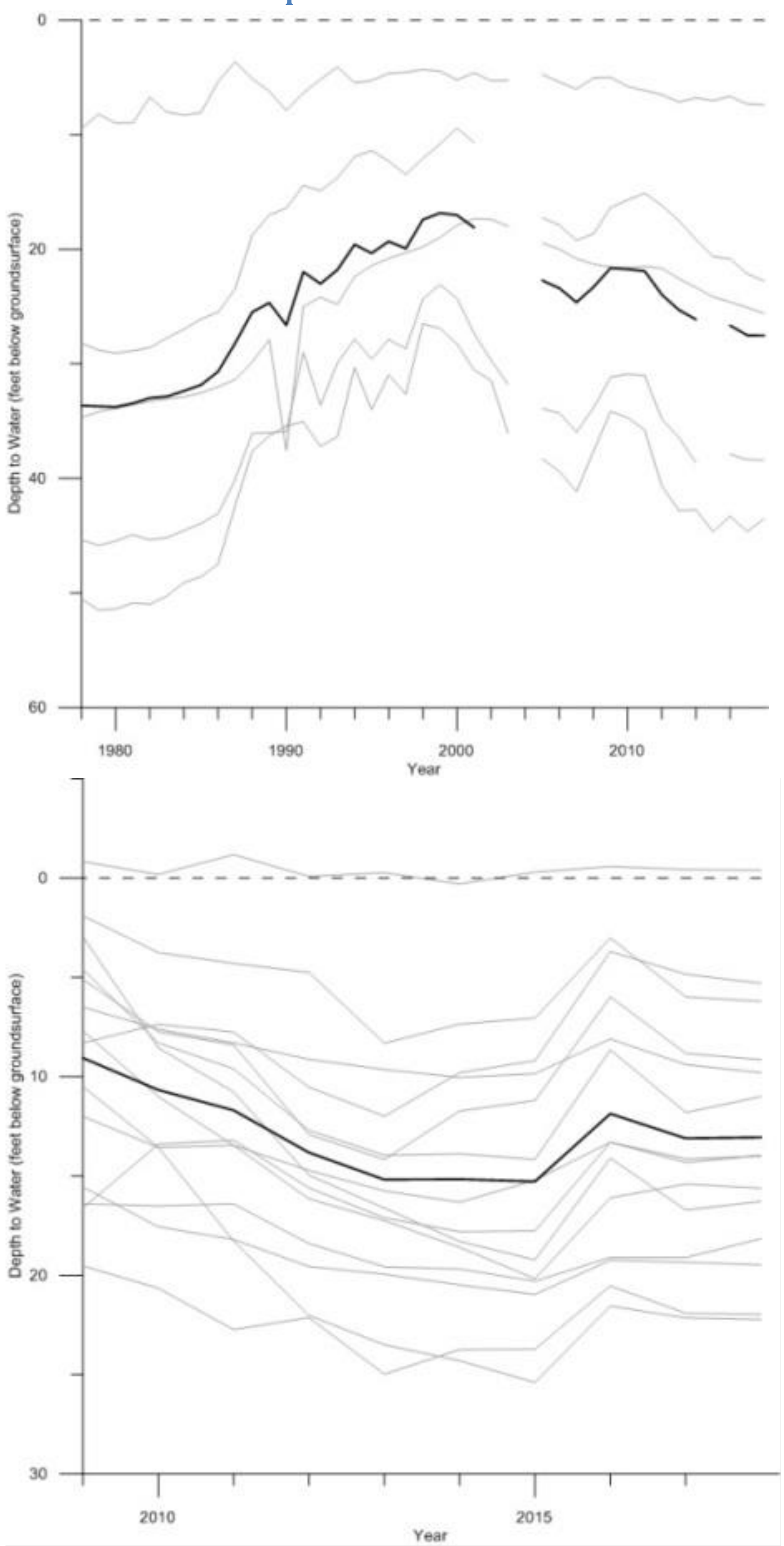


Figure 35. ENID (N=5; 1978-2018; top) and SFAR (N-14; 2009-2018; bottom).

Alluvial & Terrace Aquifers: Southwest and West Central Climate Divisions

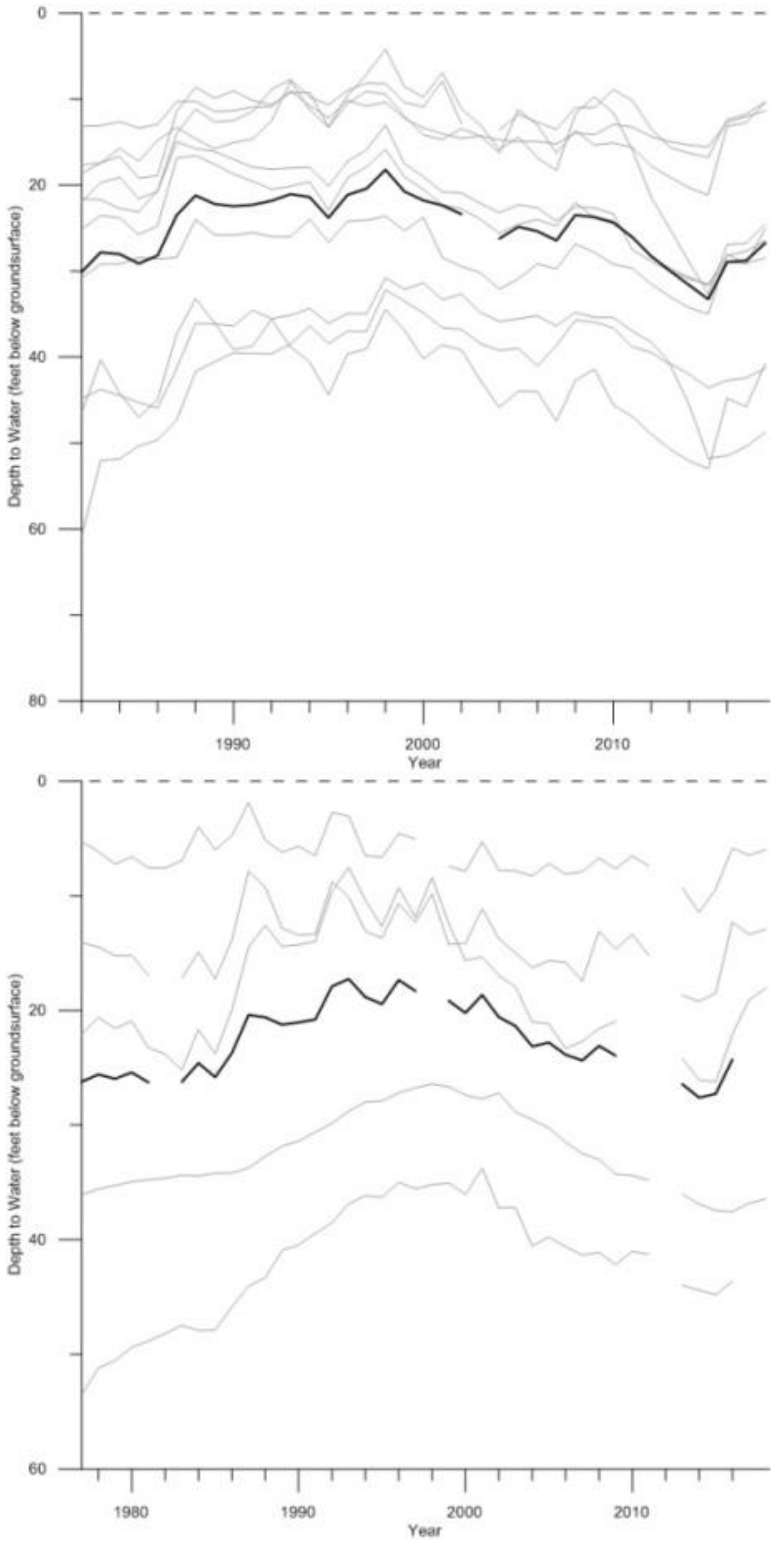


Figure 36. NFRR (N=10; 1982-2018; top) and TILL (N=5; 1977-2018; bottom).

Bedrock Aquifers: Eastern Oklahoma

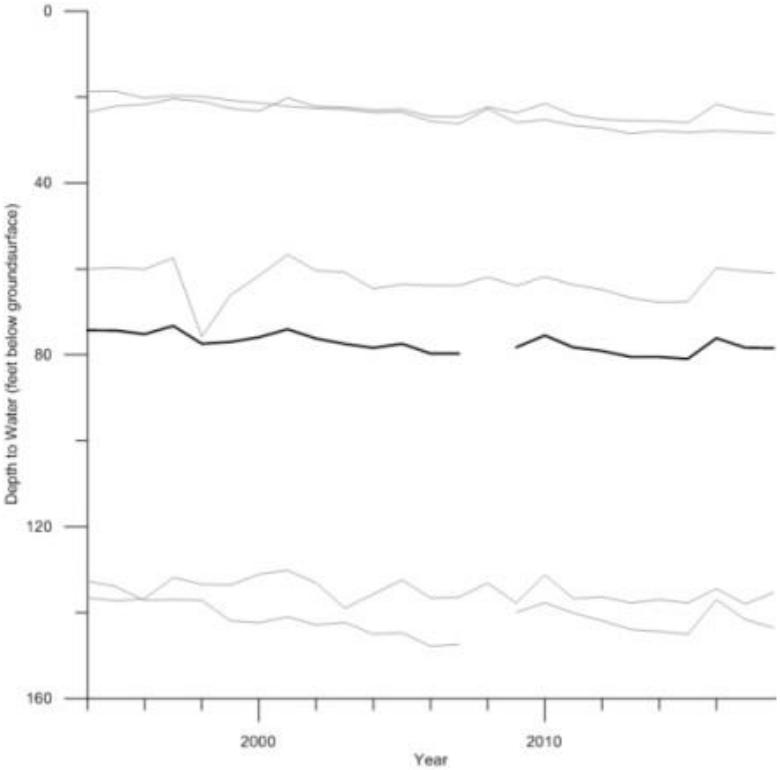
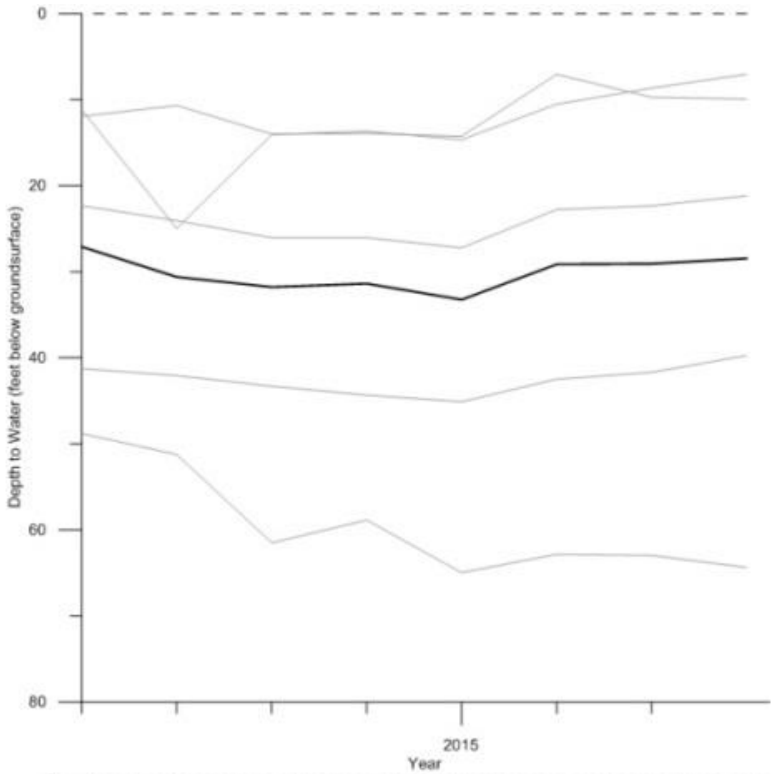
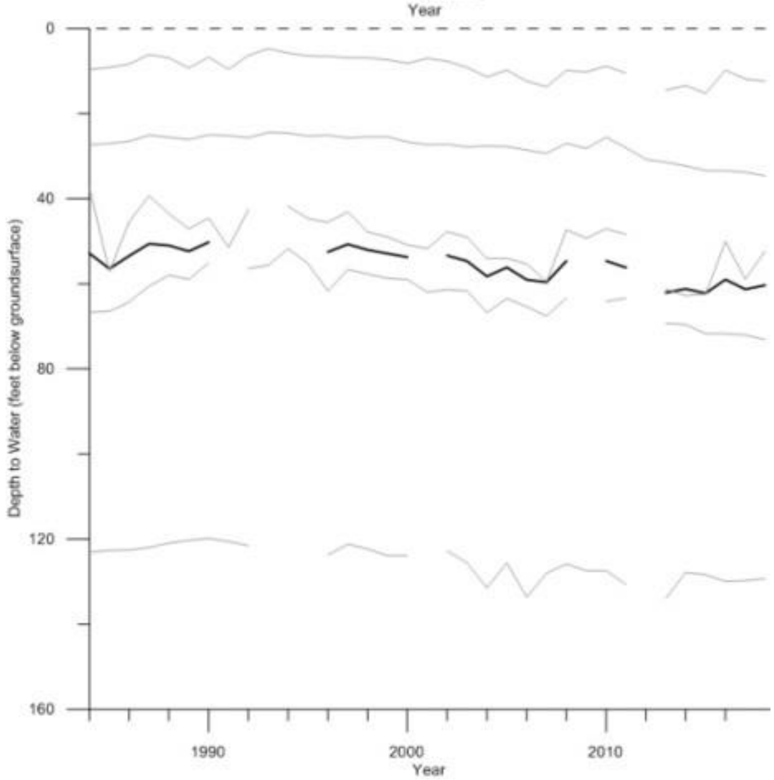


Figure 37. ALRS subcrop (N=5; 1994-2018).

Bedrock Aquifers: Central and Western Oklahoma





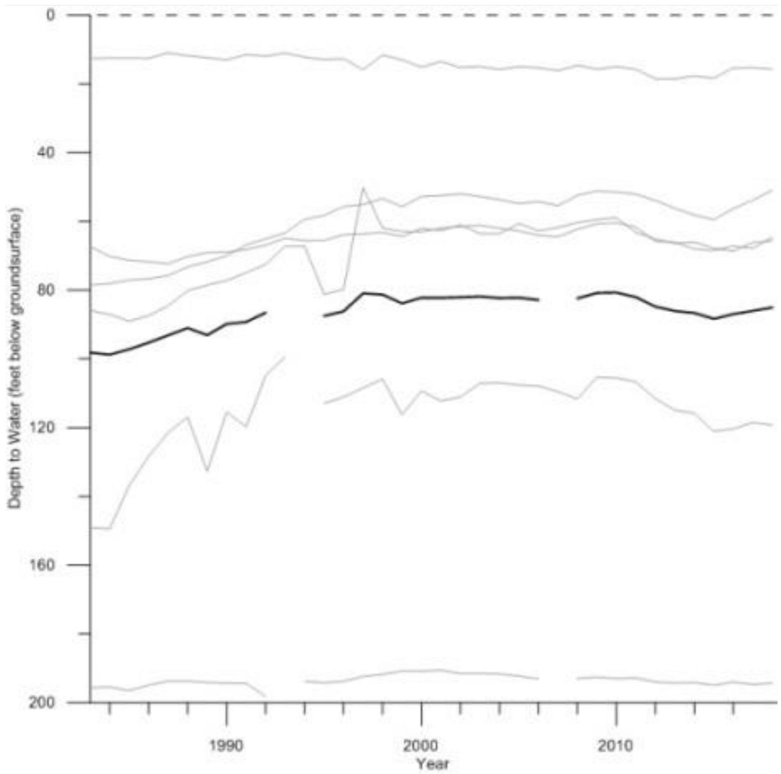


Figure 38. ELKC (N=5; 2011-2018; top), GSWF (N=5; 1984-2018; center) and RSPG (N=6; 1983-2018; bottom).

Bedrock Aquifers: Panhandle and Northwestern Oklahoma

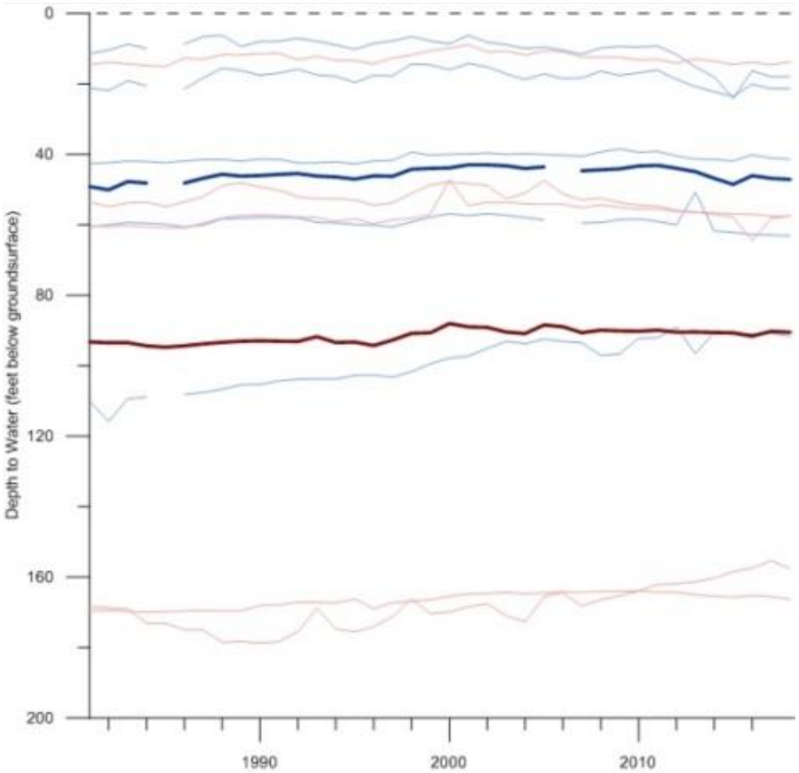
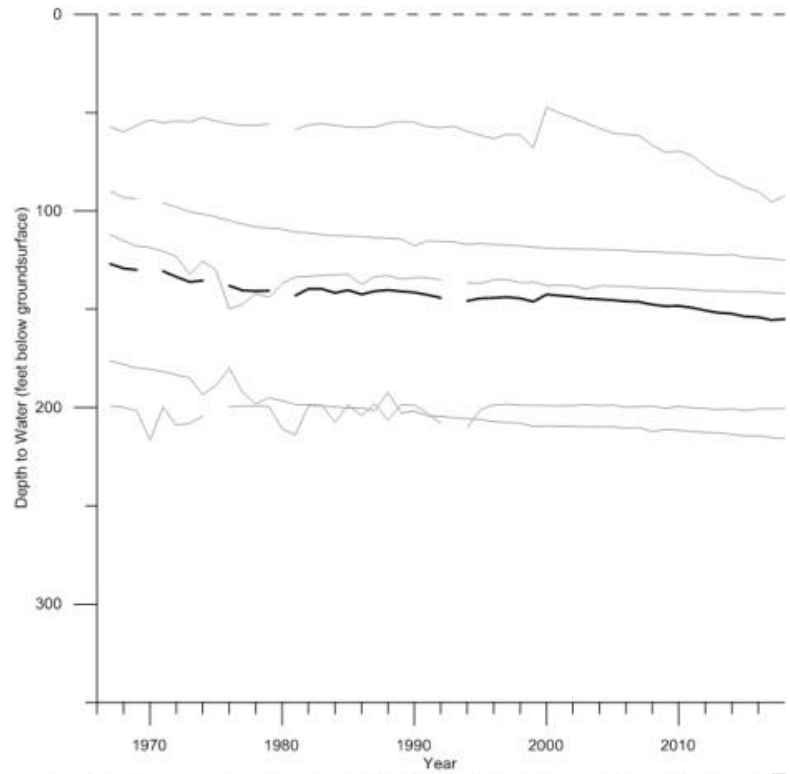
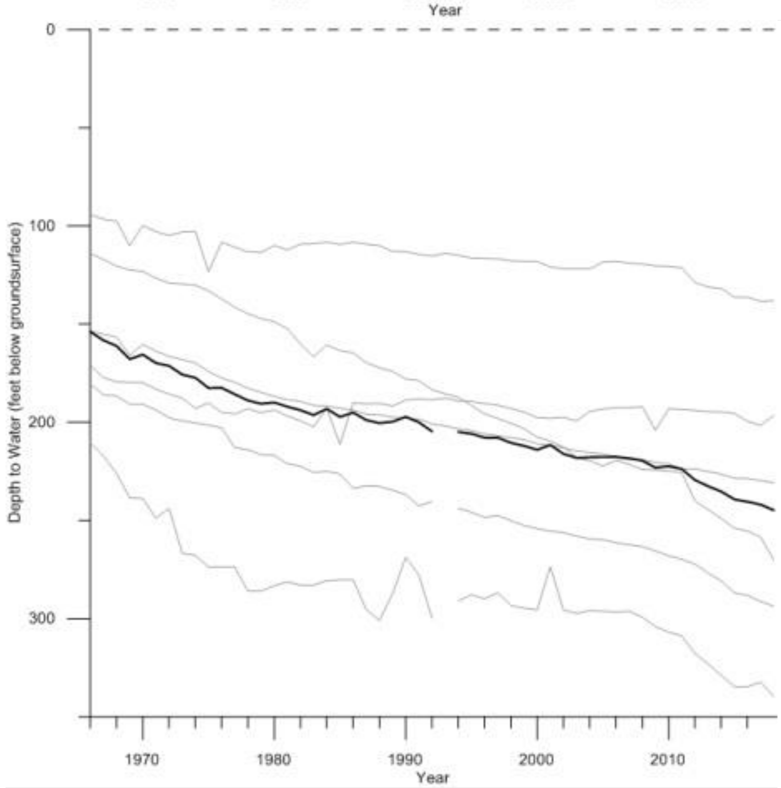


Figure 39. OGLLNW north (N=5; red lines) and south (N=5; blue lines) of the Canadian River (1981-2018).



0
100
200
300
Depth to Water (feet below groundsurface)
1970
1980
1990
2000
2010
Year



0
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Depth to Water (feet below groundsurface)
1970
1980
1990
2000
2010
Year

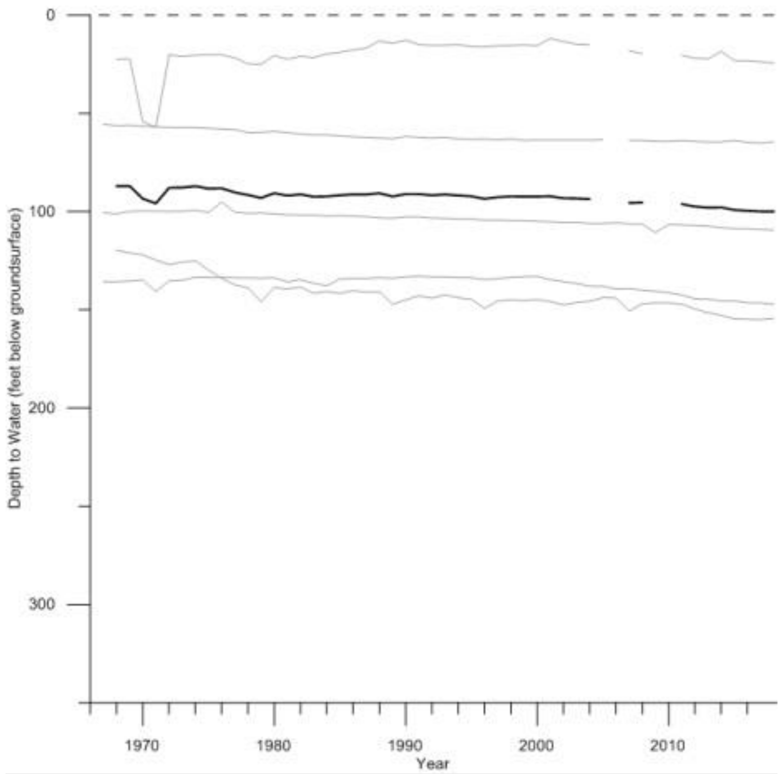


Figure 40. OGLLP-Cimarron (N=5; 1967-2018; top), Texas (N=6; 1966-2018; center), and Beaver (N=5; 1968-2018; bottom) Counties.

Trend Network Hydrographs

Implementation of the water level trend network allows for more fine-tuned representation of changing water levels than is possible with annual measurements. Wells with no data gaps are selected to present a composite average seasonal water level. The composite hydrographs that follow represent the average seasonal water level of all major aquifers with at least five years of data.

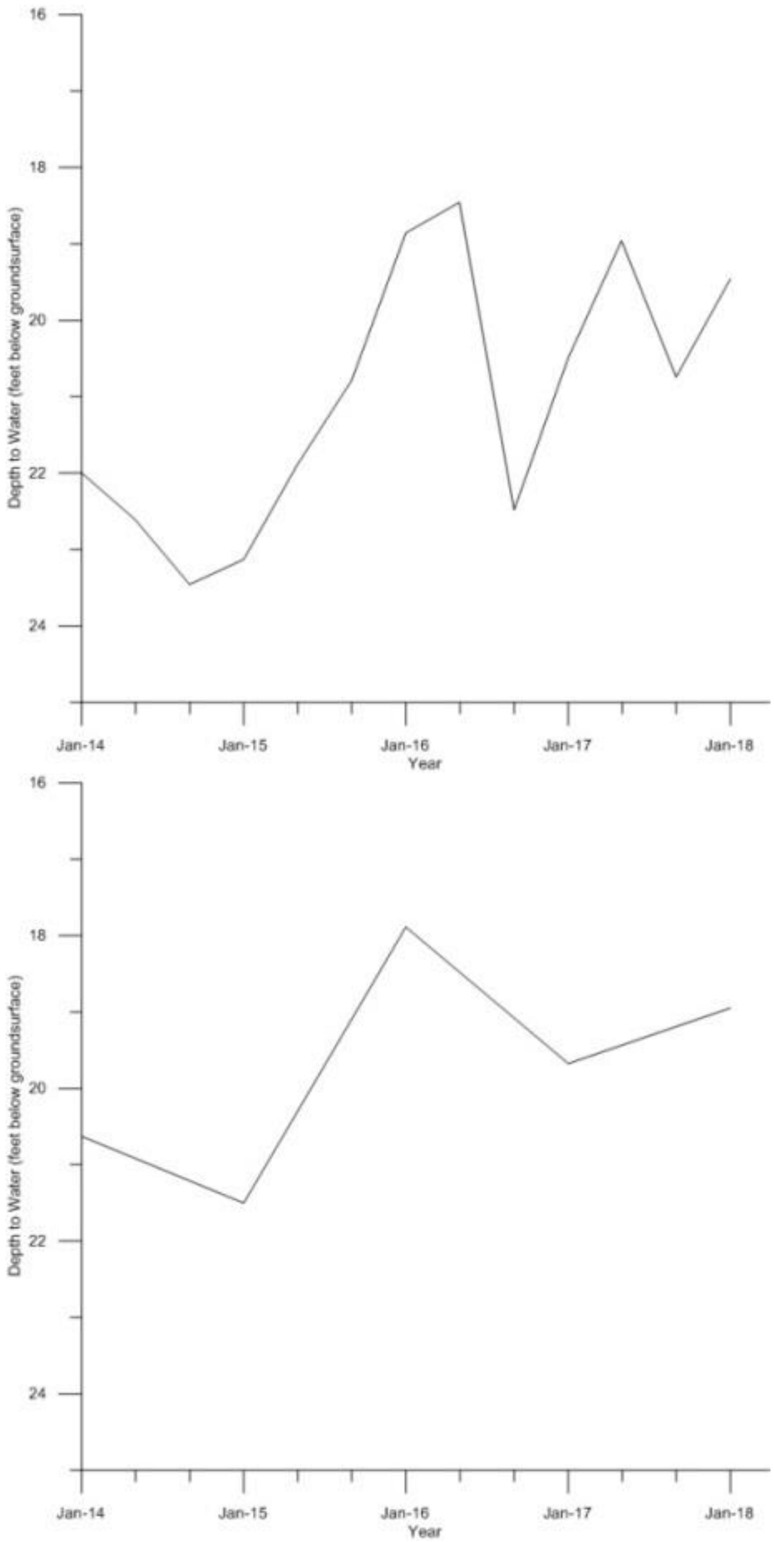


Figure 41. Average water level in the GMAP trend water level network on a seasonal (top, N=9) and annual (bottom, N=29) basis for CNDN (2014-2018).

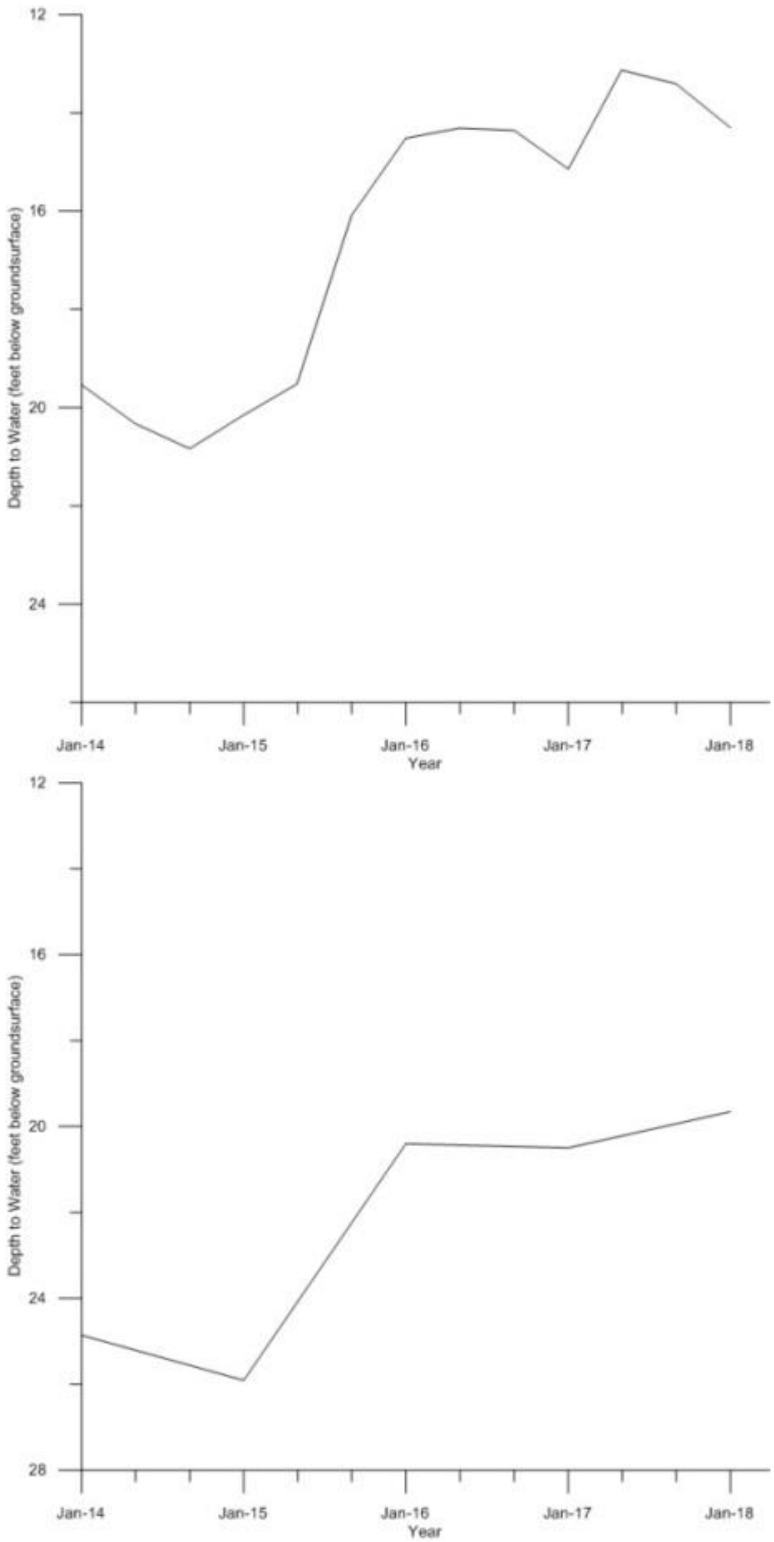


Figure 42. Average water level in the GMAP trend water level network on a seasonal (top, N=6) and annual (bottom, N=22) basis for ELKC (2014-2018).

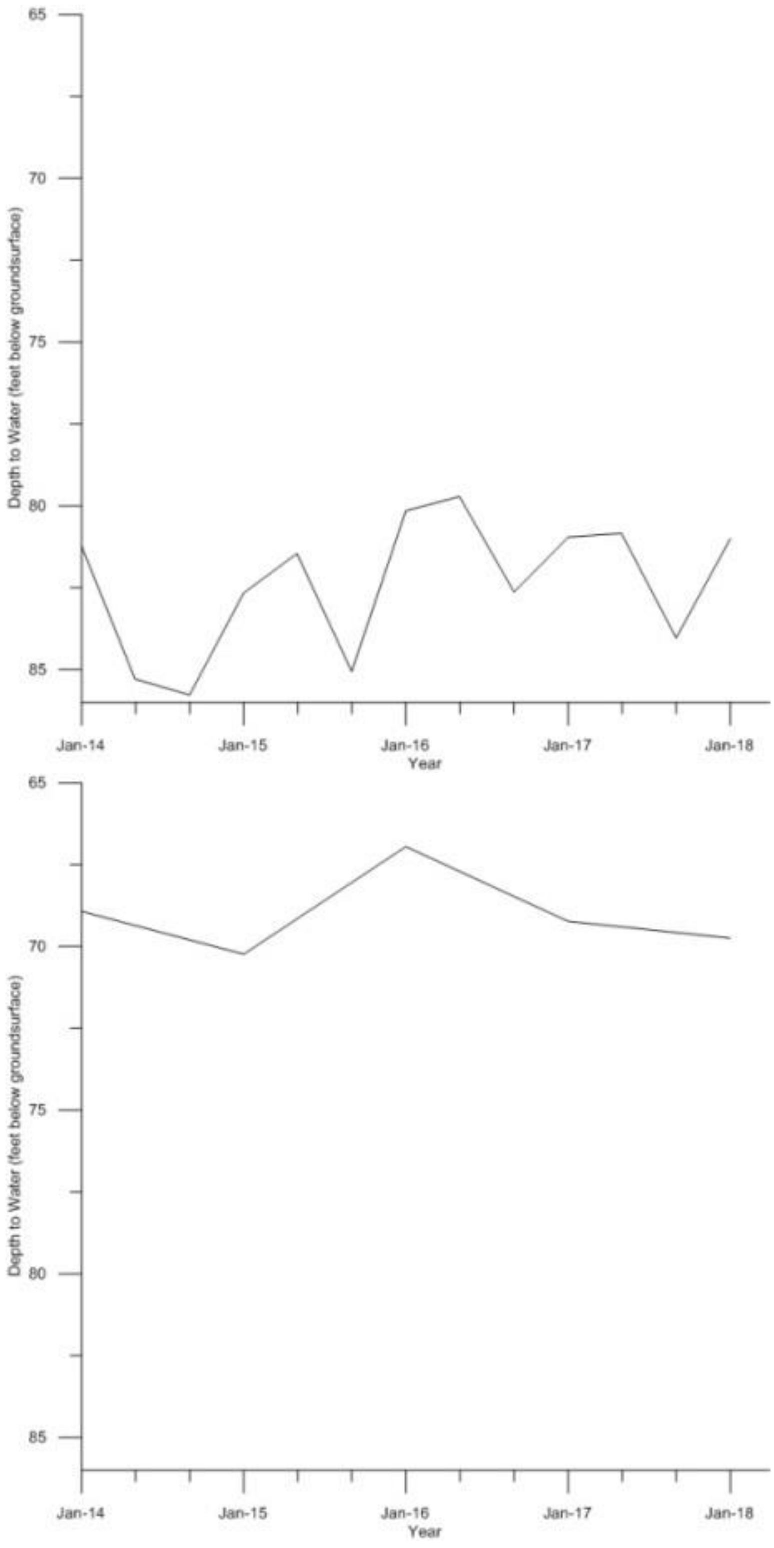


Figure 43. Average water level in the GMAP trend water level network on a seasonal (top, N=19) and annual (bottom, N=44) basis for GSWF (2014-2018).

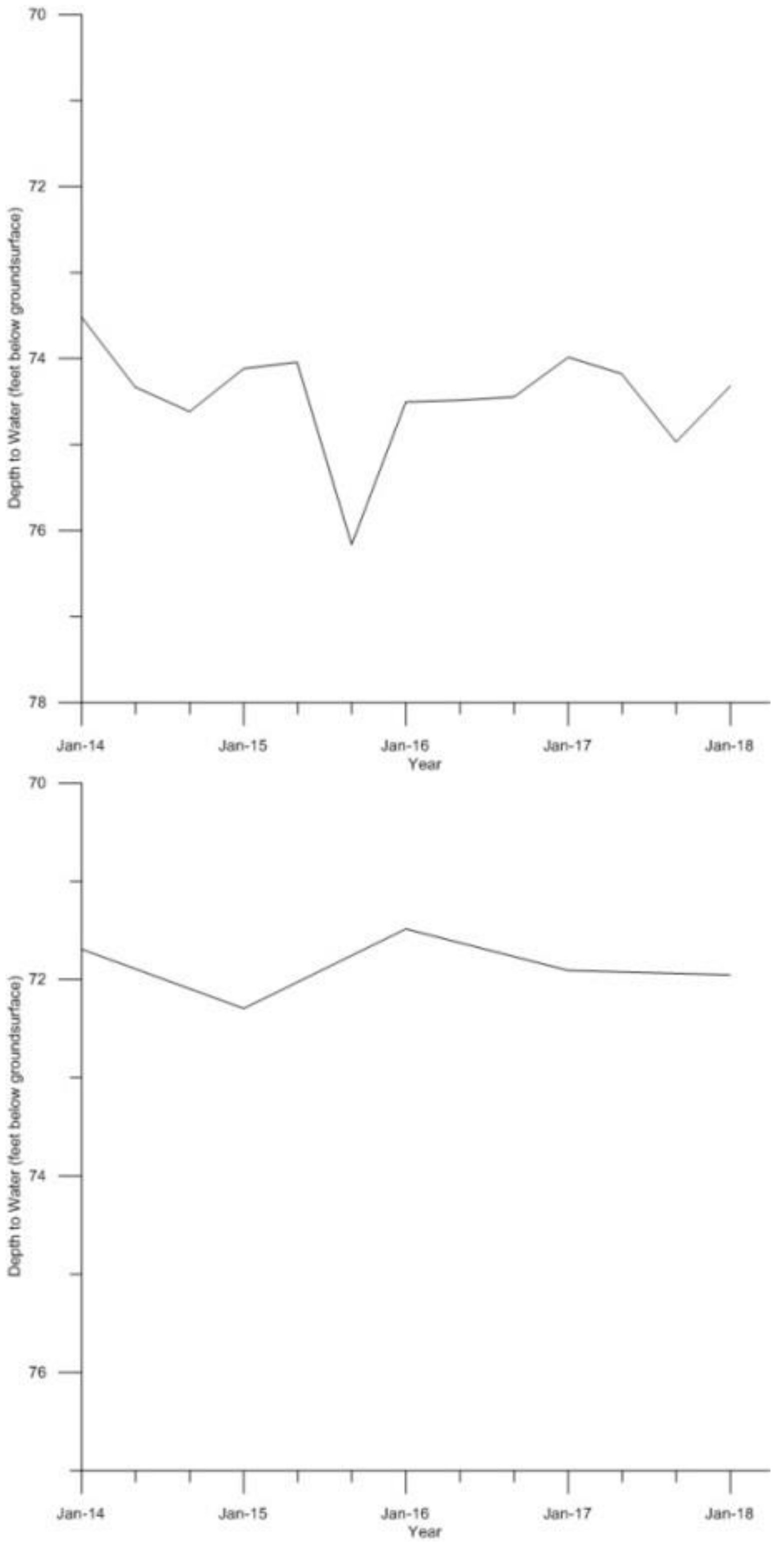


Figure 44. Average water level in the GMAP trend water level network on a seasonal (top, N=11) and annual (bottom, N=56) basis for OGLLNW (2014-2018).

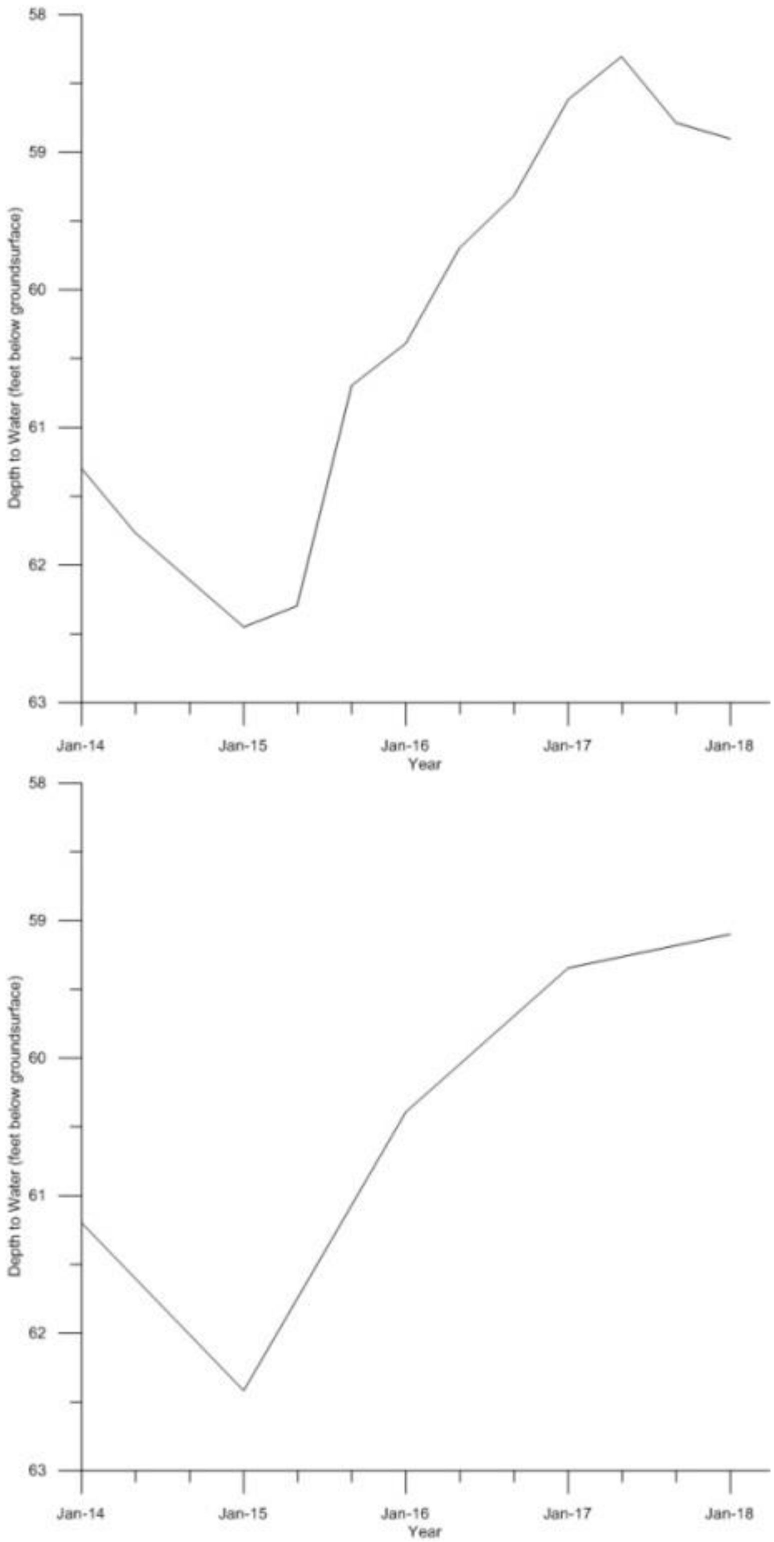


Figure 45. Average water level in the GMAP trend water level network on a seasonal (top, N=21) and annual (bottom, N=75) basis for RSPG (2014-2018).

Period of Record Hydrographs

Period of record hydrographs allow for a longer-term view of water levels than can be obtained through a composite hydrograph. Care is taken when presenting these water levels to ensure that the hydrograph conforms to expected results based on lithology, climate, and other individual or composite hydrographs (where available). The individual hydrographs that follow, grouped by aquifer type and climate division, represent single entry points into the aquifer with the longest period of record.

Karst Aquifers

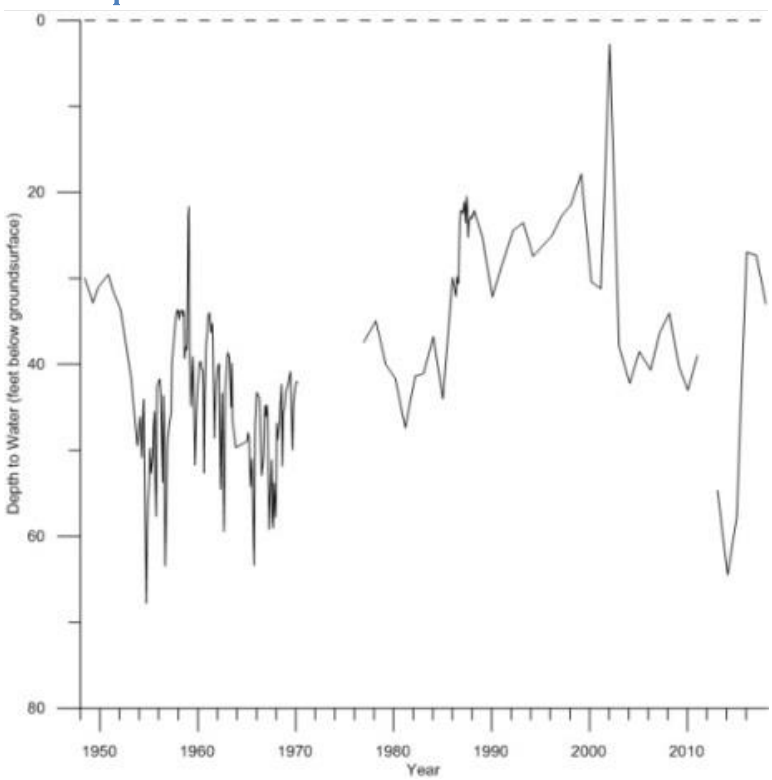


Figure 46. DCBG, Jackson County (1948-2018).

Alluvial & Terrace Aquifers: Multiple Climate Divisions

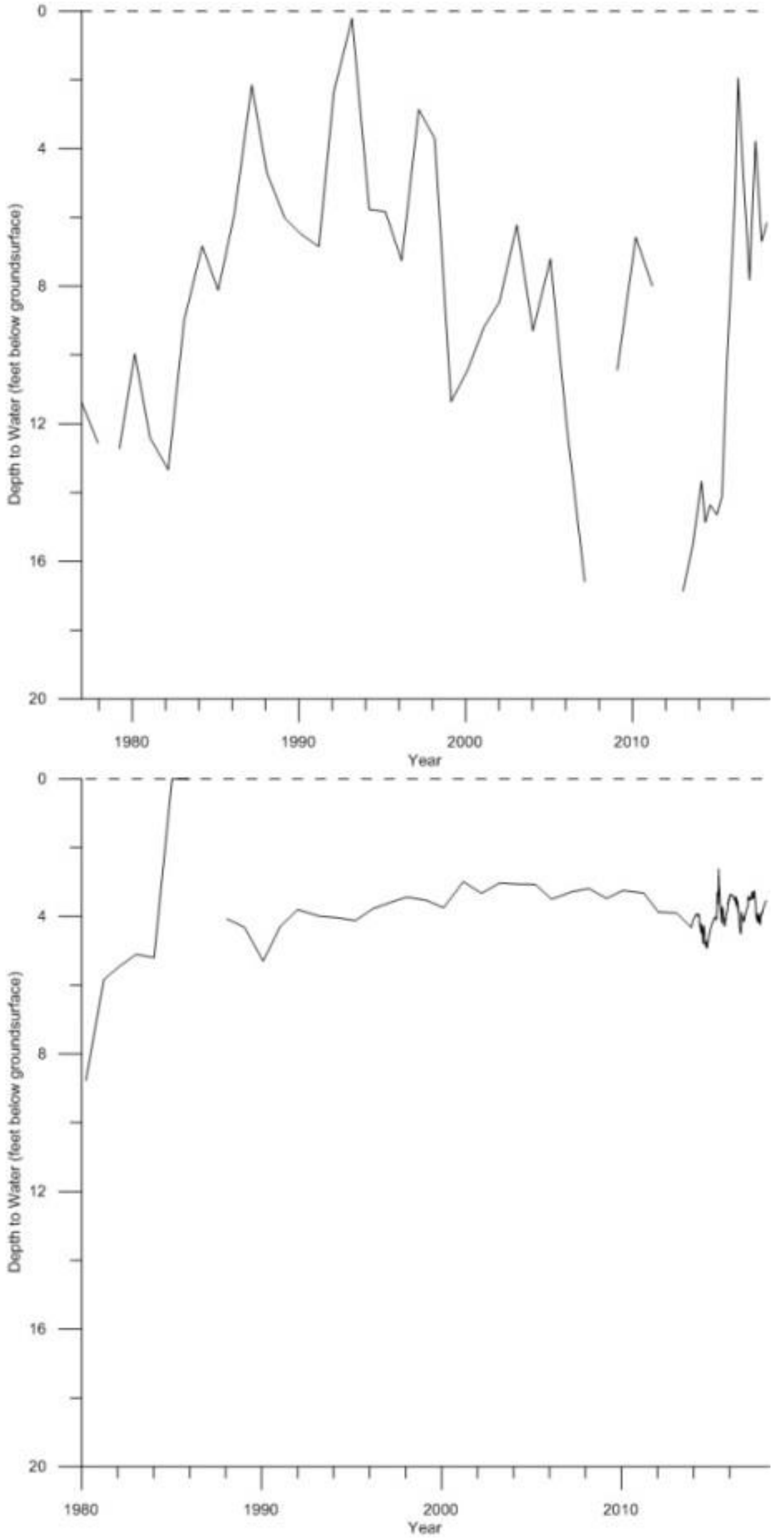
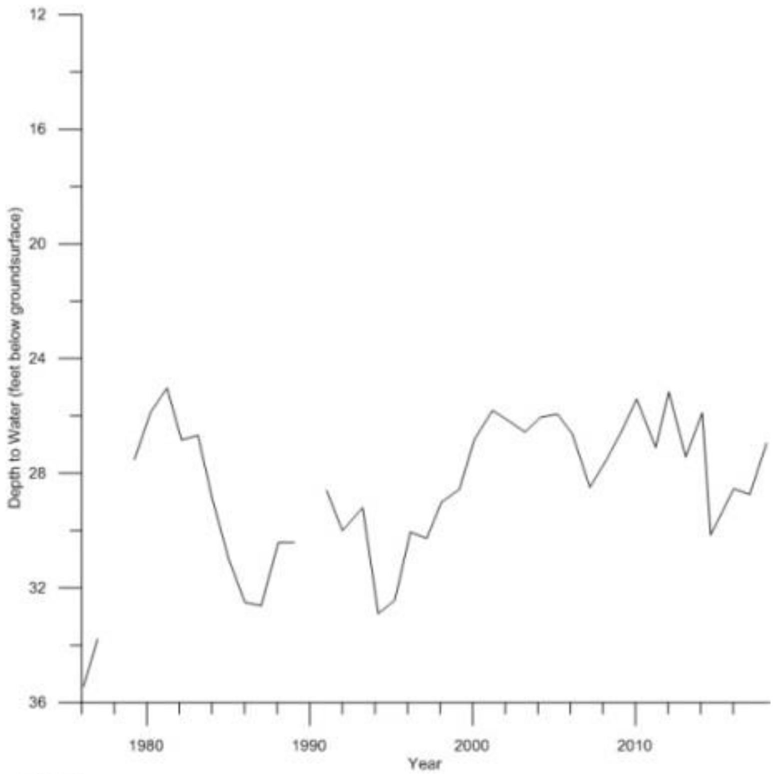


Figure 47. CNDN, McClain County (1977-2018; top) and Roger Mills County (1980-2018; bottom).



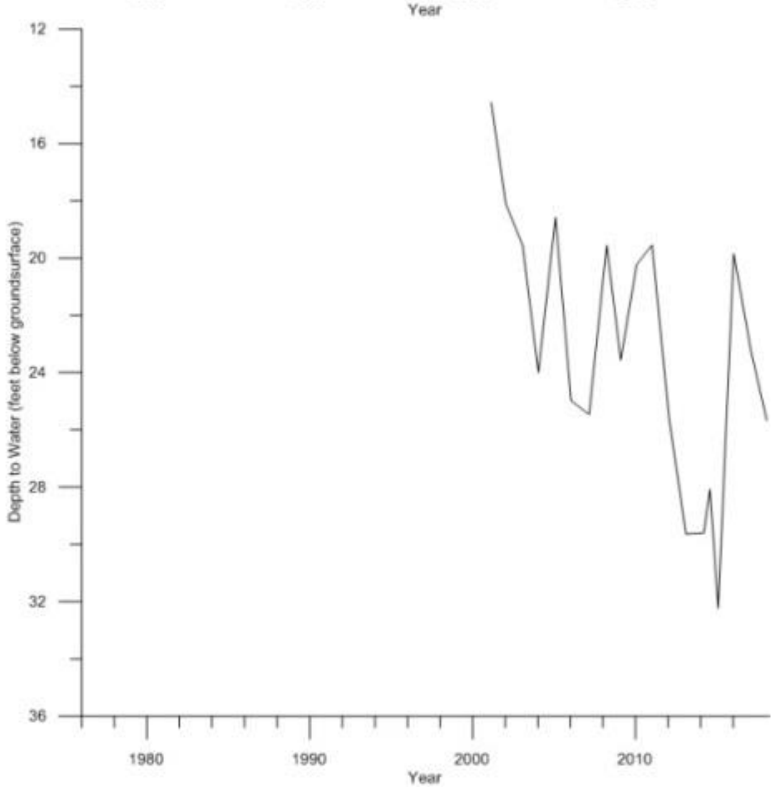


Figure 48. WASH, Roger Mills County (1976-2018; top) and Garvin County (2001-2018; bottom).

Alluvial & Terrace Aquifers: Panhandle Climate Division

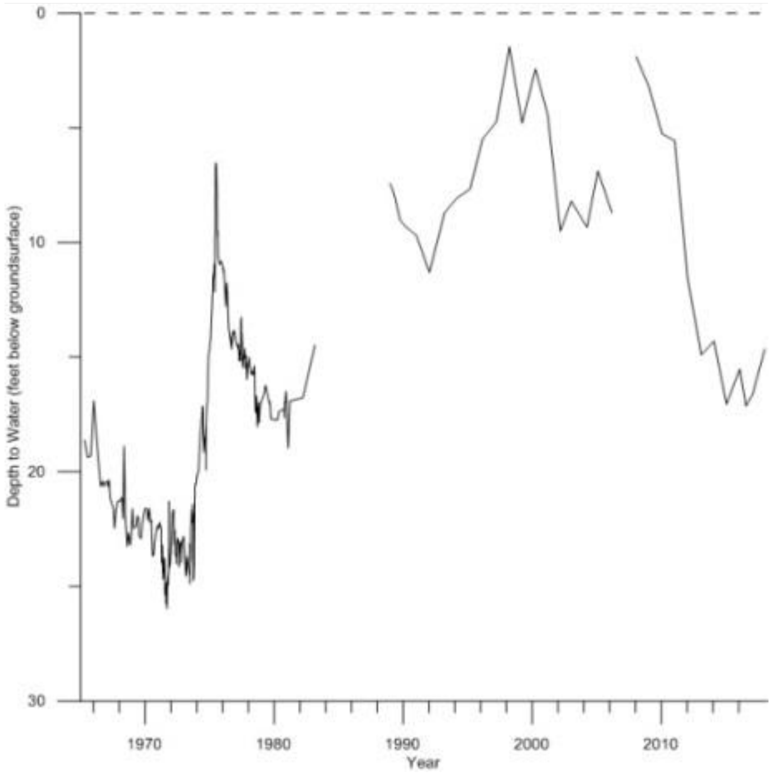
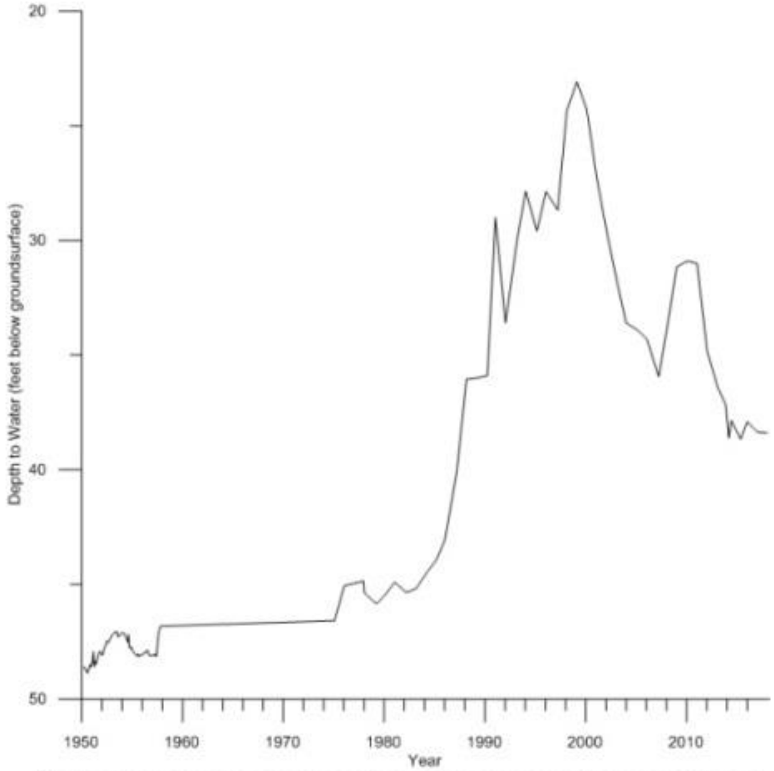


Figure 49. CMRN, Major County (1965-2018).

Alluvial & Terrace Aquifers: North Central Climate Division



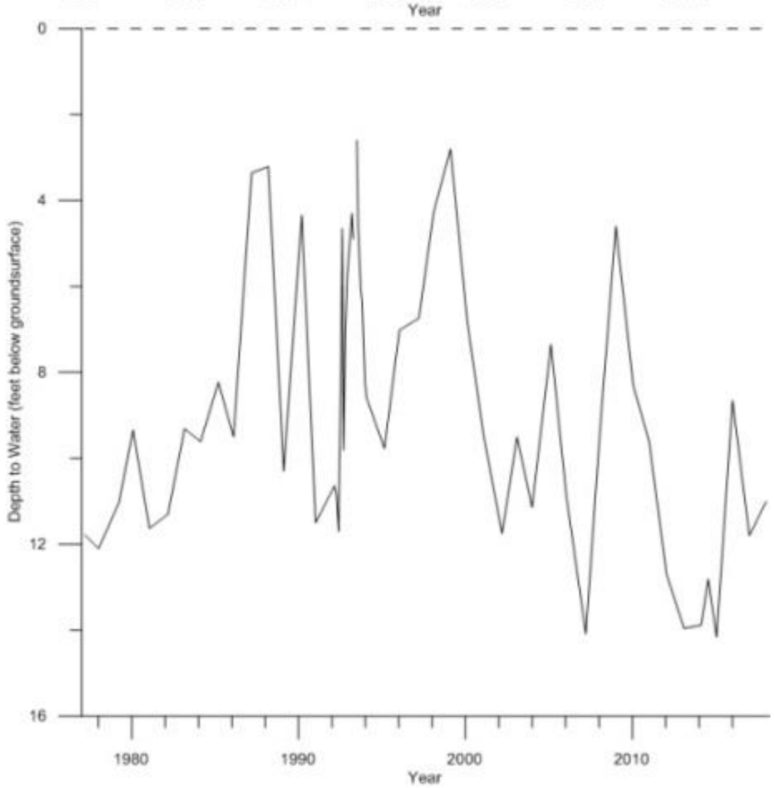


Figure 50. ENID, Garfield County (1950-2018; top) and SFAR, Grant County (1977-2018; bottom).

Alluvial & Terrace Aquifers: Southwest and West Central Climate Divisions

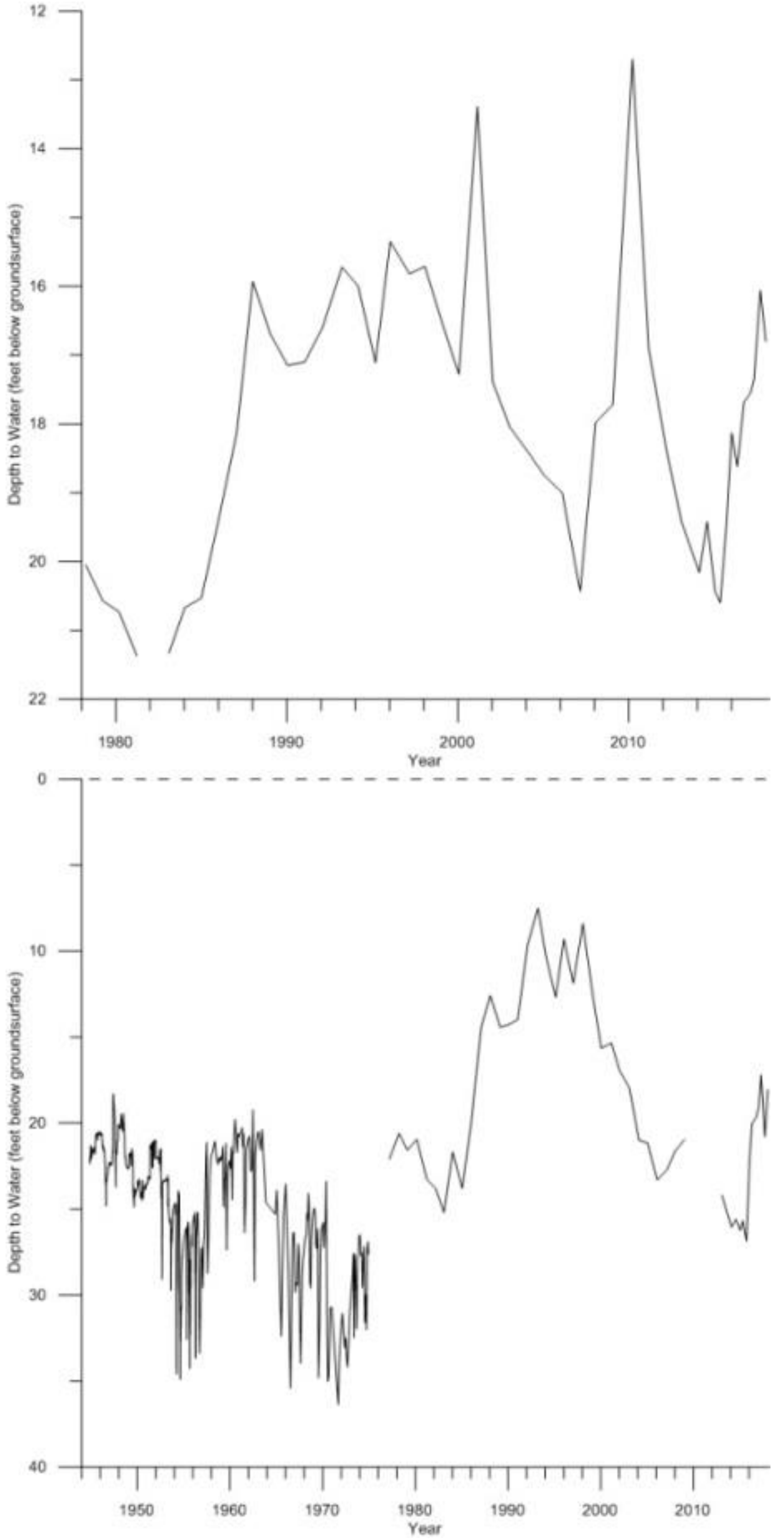


Figure 51. NFRR, Kiowa County (1978-2018; top) and TILL, Tillman County (1944-2018; bottom).

Alluvial & Terrace Aquifers: South Central Division

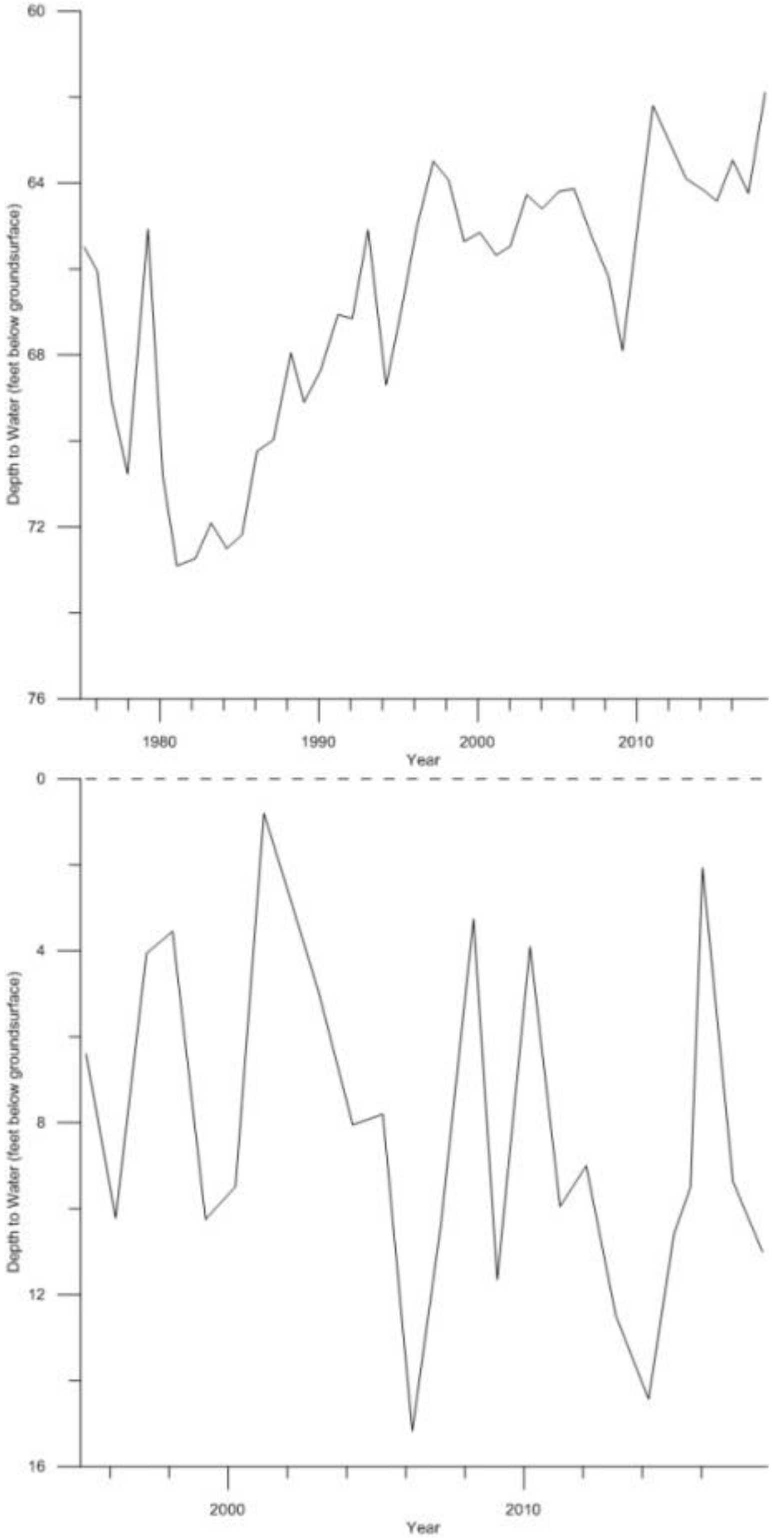
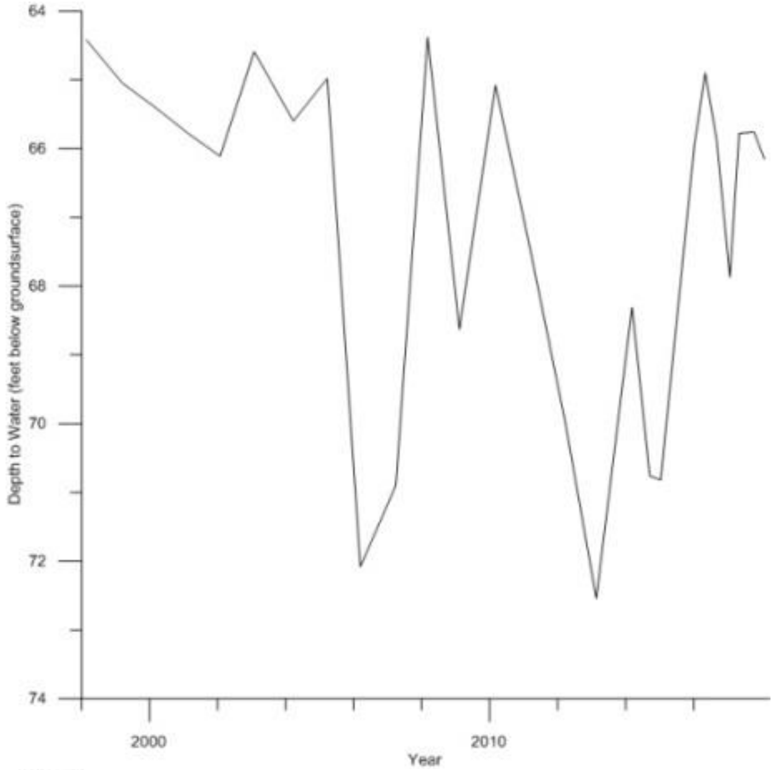


Figure 52. GRTY, Garvin County (1975-2018; top) and RED, Bryan County (South Central climate division; 1995-2018; bottom).

Bedrock Aquifers: Eastern Oklahoma



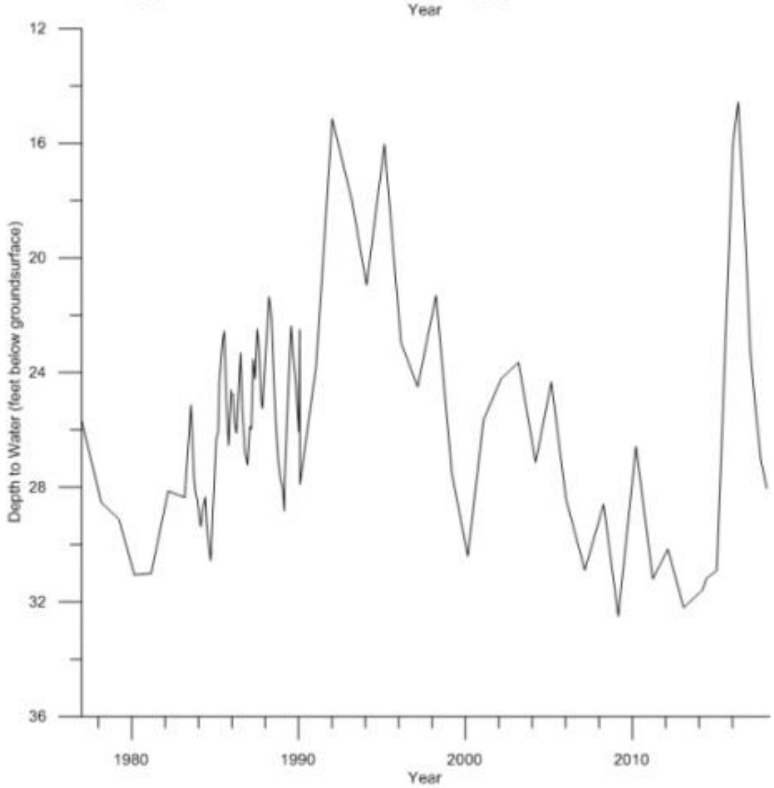


Figure 53. ADVM-unconfined, Seminole County (1998-2018; top) and ALRS-unconfined, Johnston County (1977-2018; bottom).

Bedrock Aquifers: Panhandle and Northwestern Oklahoma

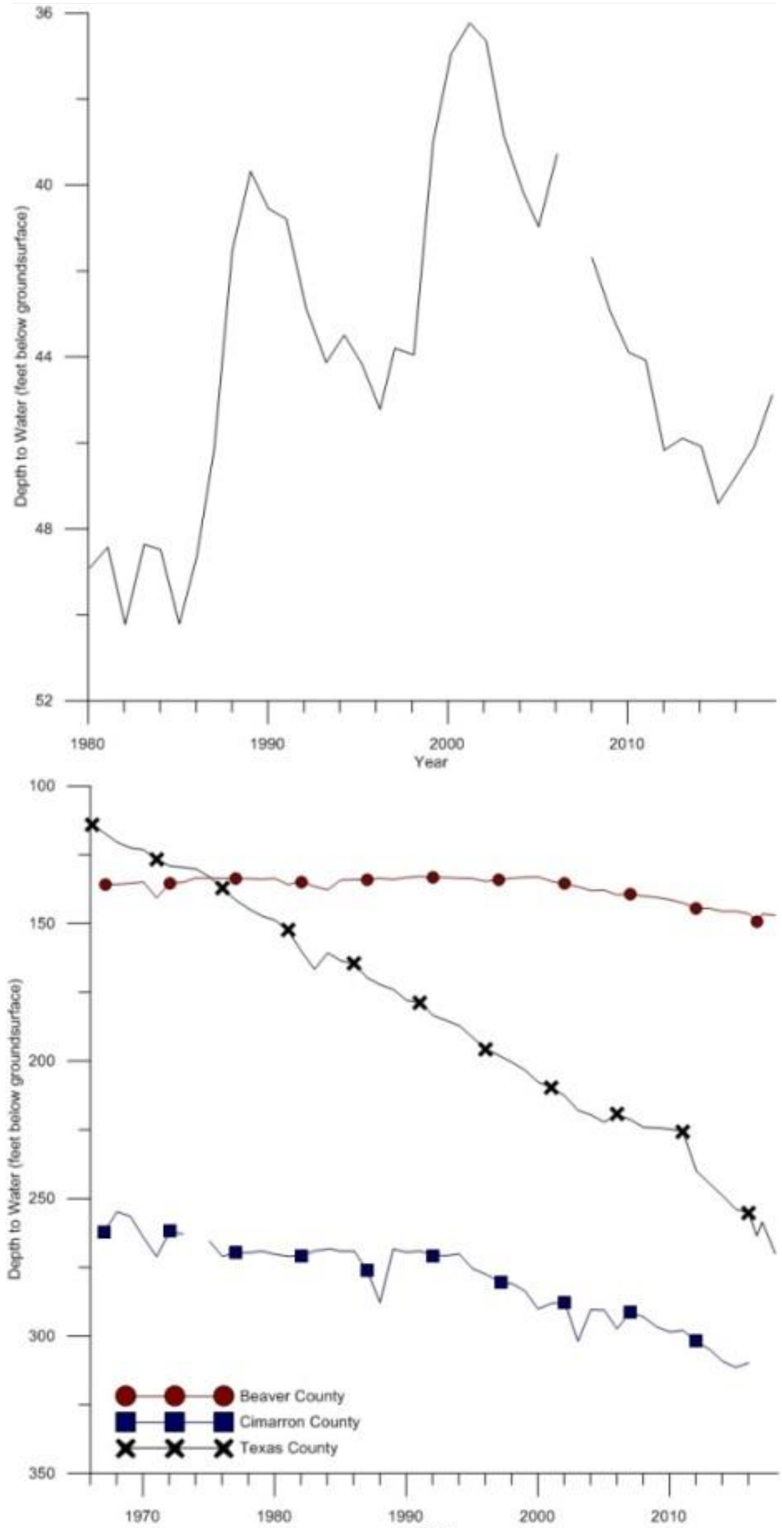


Figure 54. OGLLNW, Ellis County (1980-2018; top) OGLLP (by county; 1966-2018; bottom).

Bedrock Aquifers: Central and Western Oklahoma

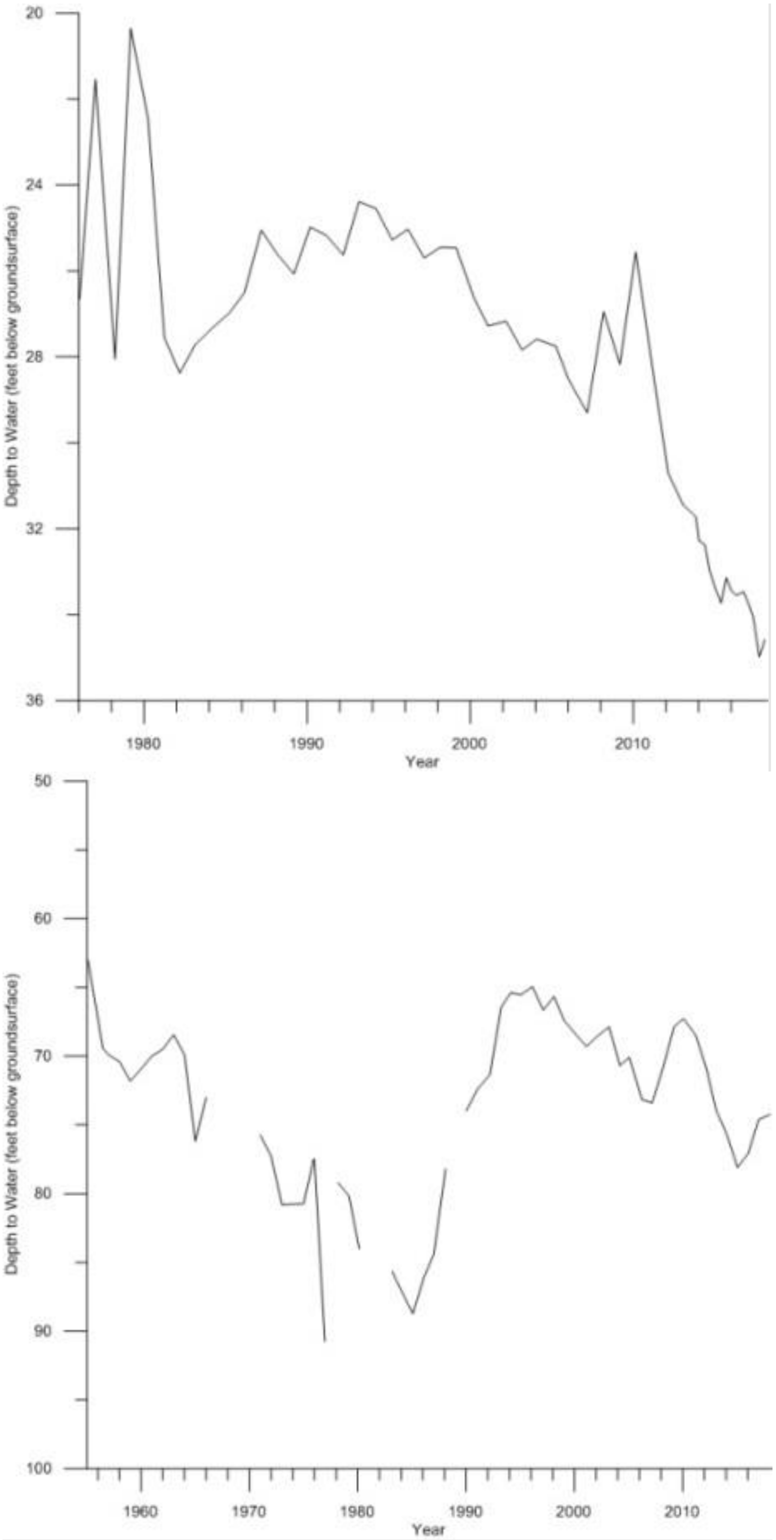
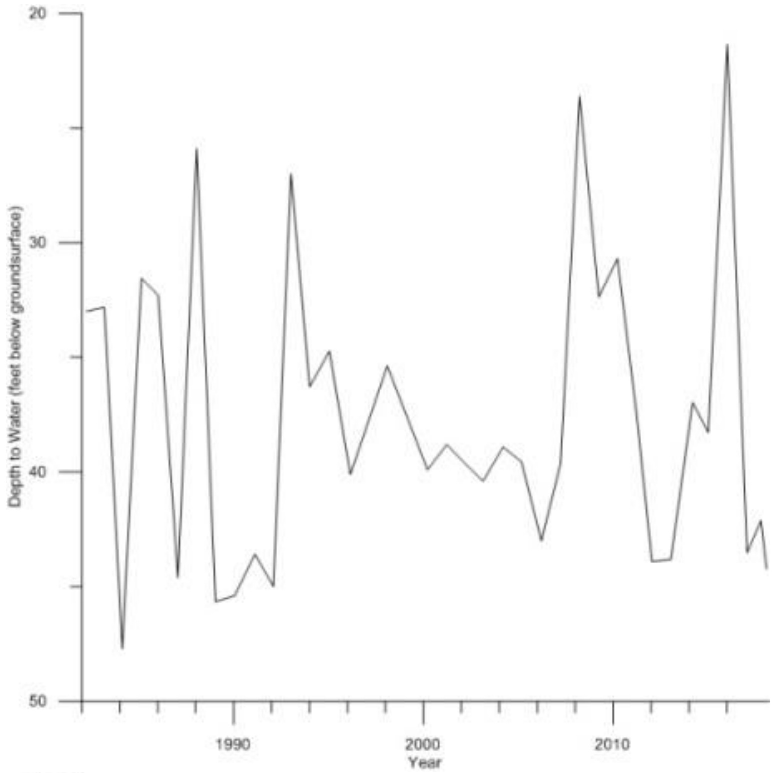
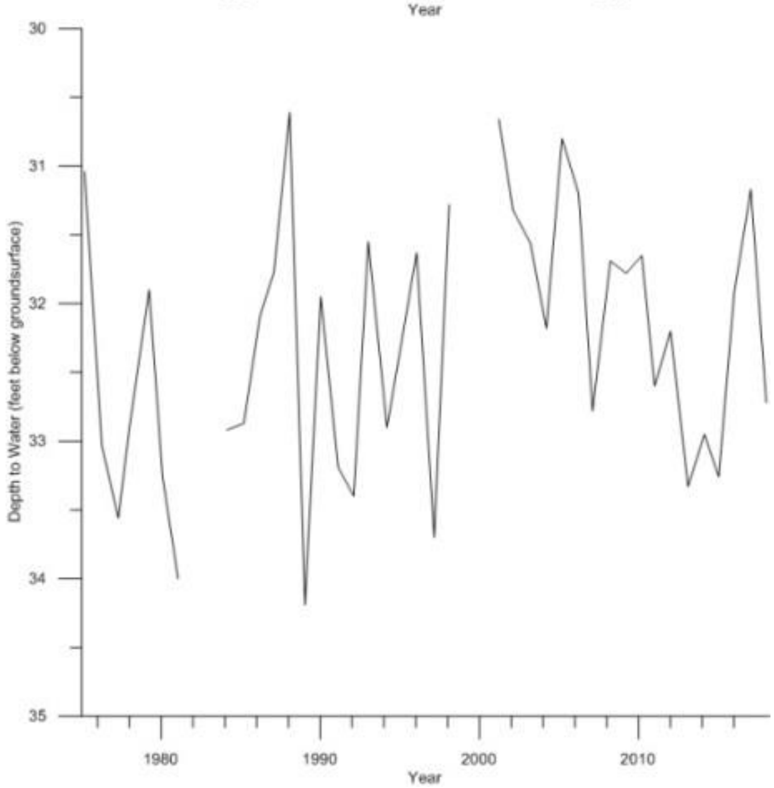


Figure 55. GSWF, Oklahoma County (1976-2017; top) and RSPG, Caddo County (1955-2018; bottom).

Minor Aquifers





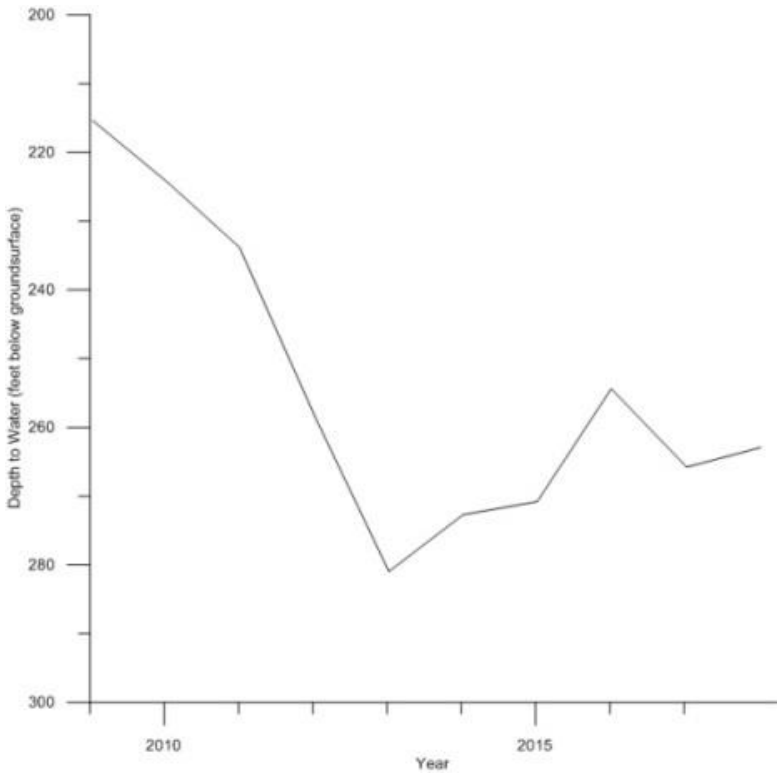


Figure 56. BOON, Adair County (1982-2018; top). Chickasha Minor A&T, Kay County (1975-2018; center). DAKD, southwest Cimarron County (2009-2018; bottom).

Trend Water Quality Network

Introduction

To continue OWRB's efforts to better characterize groundwater beneficial uses and to help promote better groundwater use guidelines for the State of Oklahoma, the GMAP is beginning a water quality trend network in the spring of 2019. This network is intended to document current conditions, document change in condition over time, assess beneficial use capacity, track water availability, monitor change in the aquifer storage over time, and inform decision makers as to the extent and/or limits that groundwater can augment future water supply.

Network Design

The number of sites to be monitored in each aquifer by this network was based on areal extent, hydrogeology, baseline water quality sampling results and program costs. Trend water quality sites will be visited on a rotating basis (1, 3 or 5 years) based on their natural vulnerability to contamination (OWQS Chapter 45-7-3(c), Appendix D, Table 1). Aquifers classified with very high or high vulnerability will be sampled annually; aquifers with moderate vulnerability will be sampled once every three years; and aquifers with low vulnerability will be sampled once every 5 years. The sampling rotation pattern (sampling frequency) will be directed by the vulnerability classification scheme shown in Figure 59 and Table 7. Some important major bedrock aquifers (RBDX and ABTH) will not be monitored at the outset of the implementation of the trend water quality network due to lack of wells. In order to characterize and describe the water quality of these aquifers in a meaningful way, 15-20 wells would have to be drilled across the spatial extent of the RBDX and 10-12 wells across the spatial extent of the ABTH, however due to extremely high well drilling costs this was deemed unfeasible. Target well depths would typically be in excess of more than 1,000 feet for both aquifers.

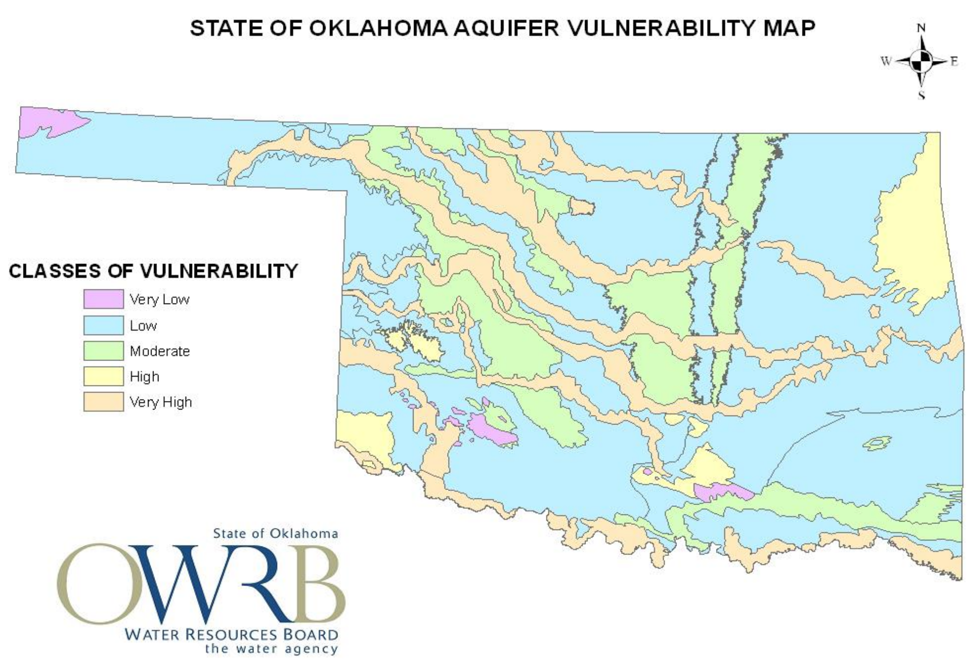


Figure 57. Oklahoma's aquifer vulnerability designations as provided by OWRB's Water Quality Standards.

Vulnerability of an aquifer is characterized by depth to water, permeability of the aquifer and rate of recharge among other factors. For aquifers on a 3 or 5 year rotation, 50 percent of the network wells will be sampled over two years followed by either a one year or three year cessation of monitoring. For the subset of wells sampled over a two year period, spatial balance will be maintained for both sampling years.

Baseline wells were prioritized over new wells for inclusion into the trend network. However, the random nature of selecting the baseline wells did not always yield a uniform spatially distributed network across an aquifer so gap wells were identified and inserted into the trend network to achieve spatial representativeness. Any well sampled in the baseline period is deemed to be representative of the aquifer, and therefore eligible to be included in the water quality trend network. Wells added after the baseline evaluation will need to be compared against the active network to determine representativeness before being allowed to be kept and characterized with the water quality trend network.

As of the writing of this report, no full seasonality component has been written into the design of this water quality trend network. Until a full seasonality component is implemented, there will be a small sub-network of wells within each aquifer's full network that will be sampled once in the spring and once in the fall for comparability purposes. This sub-network will not be used to draw conclusions on the seasonality of water quality, but rather will serve as an exploratory study on how to best implement a full seasonal component into the GMAP's water quality trend network.

Table 7. Projected water quality trend sampling schedule.

Aquifer	Classification	N	Year 20__														
			19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
ABSMP	1	8	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
ARKS	1	10	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
BNCR	1	13	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
CMRN	1	12	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
CNDN	1	10	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
ENID	1	5	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
GRTY	1	5	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
NFRR	1	9	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
REDR	1	13	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
SFAR	1	10	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
SFRR	1	5	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
TILL	1	5	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
WASH	1	12	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
ALRS (oc)-1	3	6	y	n	n	y	n	n	y	n	n	y	n	n	y	n	n
ALRS (oc)-2	3	6	n	y	n	n	y	n	n	y	n	n	y	n	n	y	n
ELKC-1	3	6	y	n	n	y	n	n	y	n	n	y	n	n	y	n	n
ELKC-2	3	6	n	y	n	n	y	n	n	y	n	n	y	n	n	y	n
GSWF-1	3	15	y	n	n	y	n	n	y	n	n	y	n	n	y	n	n
GSWF-2	3	15	n	y	n	n	y	n	n	y	n	n	y	n	n	y	n
RSPG-1	3	15	y	n	n	y	n	n	y	n	n	y	n	n	y	n	n
RSPG-2	3	15	n	y	n	n	y	n	n	y	n	n	y	n	n	y	n
ADVM-1	3	10	y	n	n	y	n	n	y	n	n	y	n	n	y	n	n
ADVM-2	3	10	n	y	n	n	y	n	n	y	n	n	y	n	n	y	n
OGLLNW-1	3	15	y	n	n	y	n	n	y	n	n	y	n	n	y	n	n
OGLLNW-2	3	15	n	y	n	n	y	n	n	y	n	n	y	n	n	y	n
OGLLP-1	5	15	n	y	n	n	n	n	y	n	n	n	n	y	n	n	n
OGLLP-2	5	15	n	n	y	n	n	n	n	y	n	n	n	n	y	n	n
OGLLP-3	5	15	n	n	n	y	n	n	n	n	y	n	n	n	n	y	n
OGLLP-4	5	15	n	n	n	n	y	n	n	n	n	y	n	n	n	n	y
YEARLY TOTALS			184	199	132	199	199	117	199	199	132	199	184	132	199	199	132

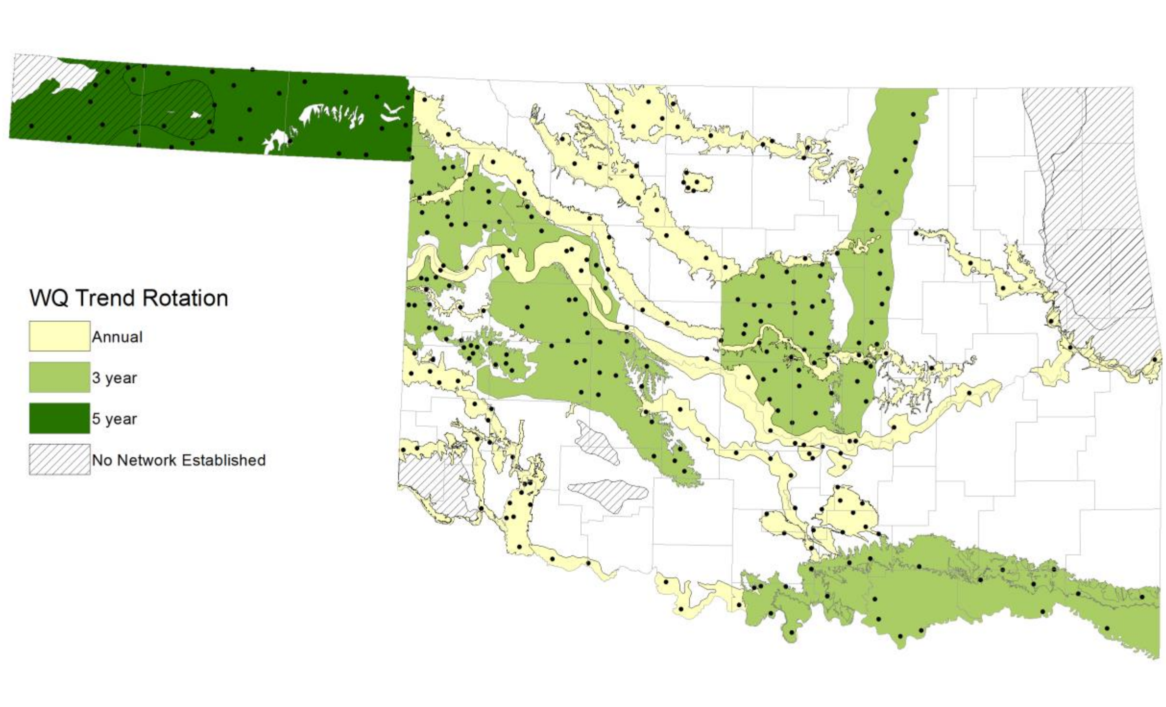


Figure 58. Projected water quality trend network by aquifer statewide.

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Table of Appendices

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Appendix A 84

Selected Descriptive Statistics for Baseline Network 84

Appendix A– Selected Descriptive Statistics for Baseline Network

		Field Parameters		Analytical Parameters						Well Use Categories							
Sites	Aquifer	pH	Hard	TDS	NO3	Ca	Na	Cl	SO4	P	I	S	D	M	N	O	DTW
34	A- CNDN	7.01	394	533	1.19	112	45.9	33.9	99.9	4	8	3	13	4	2	0	15.1
13	A- ELKC	7.26	272	349	6.37	67.2	36.5	10.6	16.5	0	1	5	7	0	0	0	22.8
47	A- GSWF	6.97	261	328	0.89	55.6	31.8	18.8	17.4	0	0	0	47	0	0	0	69.9
5	A- GRTY	6.43	202	306	2.12	50.8	33.4	36.8	13.0	0	0	2	3	0	0	0	45.5
40	A- OGLLNW	7.12	219	340	6.02	72.2	26.6	14.2	16.0	3	3	6	18	10	0	0	74.2
64	A- RSPG	7.18	302	427	4.46	78.5	25.4	11.8	61.4	6	10	7	37	4	0	0	58.9
44	B- ADVM	7.05	224	344	0.52	48.3	36.6	17.7	24.2	2	1	1	40	0	0	0	71.9
29	B- ARKS	6.63	255	385	2.42	71	24.8	11.6	26.5	4	10	0	14	0	1	0	22.5
9	B- ENID	6.75	262	566	11.3	87.5	108	61.2	75.8	3	0	0	6	0	0	0	20.2
20	B- NFRR	7.06	342	543	7.95	94.9	37.4	24.5	142	1	5	3	11	0	0	0	33.1
30	B- SFAR	7.13	348	552	4.14	76.1	94.2	55.3	66.1	1	1	10	17	1	0	0	15.8
6	B- SFRR	7.06	260	403	9.73	78.2	35.6	<10	37.8	2	3	0	1	0	0	0	47.6
8	B- TILL	7.12	390	700	13.9	78.7	164	127	103	0	4	3	1	0	0	0	28.3
31	B- WASH	7.21	1030	990	0.88	127	58.1	31.0	111	4	11	9	5	1	1	0	23.9
30	C- ALRS(o)	6.68	94	254	0.15	31.2	23.6	13.2	17.9	0	0	4	26	0	0	0	45.9
8	C-ALRS(c)	8.25	21	635	<0.05	5.1	274	33.1	76.9	2	1	1	4	0	0	0	101
18	C- ABSMP	6.91	335	335	0.99	82.3	3.6	<10	14.4	4	0	2	11	0	0	1	24.9
6	C- ABTMB	8.60	21.5	562	<0.05	2.7	212	69.7	46.6	3	1	0	2	0	0	0	75.3
41	C- BNCR	6.88	283	396	6.56	80.7	27.9	25.5	48.5	3	5	5	21	2	4	1	18.0
36	C- RED	6.72	156	296	8.52	41.8	21.9	18.1	18.1	2	4	12	18	0	0	0	24.4
4	C- WOLF	7.27	260	365	3.32	79.0	26.6	17.6	64.8	1	0	1	1	0	1	0	24.5
37	D-CMRN	7.11	263	424	9.93	75.7	35.7	33.1	37.3	6	6	6	14	1	3	1	17.3
27	D-DAKD	7.52	204	362	1.88	40.7	34.7	14.9	50.0	0	2	16	6	1	1	1	170
88	D-OGLLP	7.38	240	377	3.21	51.1	26.1	19.8	56.6	2	34	24	18	5	4	1	181
34	E-BOON	7.09	195	235	0.766	78.9	3.33	4.95	4.74	0	0	0	34	0	0	0	33.9
17	E-RBDX	7.72	141	330	<0.05	29.4	25.0	27.4	12.4	14	1	1	0	0	0	1	216

n–number of samples collected. Aquifers: CNDN-Canadian River, ELKC-Elk City Sandstone, GSWF-Garber-Wellington, GRTY-Gerty Sand Aquifer, OGLLNW-Ogallala-Northwest, RSPG-Rush Springs Sandstone, ADVM-Ada Vamoosa, ARKS-Arkansas River, ENID-Enid Isolated Terrace, NFRR-North Fork of the Red River, SFAR-Salt Fork of the Arkansas River, SFRR-Salt Fork of the Red River, TILL-Tillman Terrace, WASH-Washita River, ALRS-Antlers(o-outcrop, c-confined), ABSMP-Arbuckle-Simpson, ABTMB-Arbuckle-Timbered Hills, BNCR-North Canadian River, RED-Red River, WOLF-Wolf Creek; CMRN-Cimarron River; DAKD-Dakota-Dockum; OGLLP-Ogallala-Panhandle; BOON-Boone; RBDX-Roubidoux. Parameters: Hard–Hardness, TDS–Total Dissolved Solids, NO3–Nitrate+Nitrite as N, Ca–Calcium, Na-Sodium, Cl-Chloride, SO4-Sulfate (excepting pH, parameter units are in mg/L). Well Use Categories: P-Public Water Supply, I-Irrigation, S-Stock, D-Domestic, M-Mining, N-Industrial, O-Other. DTW–Depth to water below land surface (ft.).