DEVELOP Technical Report

Oklahoma Water Resources

Assessing Trends in Groundwater Storage for Sustainable Water Management Using GRACE and MODFLOW Datasets

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Authors: Angelina Herbert (Analytical Mechanics Associates), Ashritha Kalakuntla (Analytical Mechanics Associates), Christianah Adegboyega (Analytical Mechanics Associates), Jessica Sirois (Analytical Mechanics Associates)

Abstract:

Groundwater is a vital resource for communities in Oklahoma, upholding agricultural, municipal, and tribal livelihoods. However, it has been severely impacted by recurring droughts and sustained use for irrigation, especially in the state's western region spanning the Kiowa-Comanche-Apache (KCA) Territory. Water scarcity has contributed to widespread crop failures and increased social vulnerability, prompting the need to understand long-term groundwater trends. The Kiowa Tribe Natural Resource Department and the United States Geological Survey (USGS) Oklahoma-Texas Water Science Center track groundwater through wells and hydrological models but seek more comprehensive monitoring strategies. This study evaluated the feasibility of using NASA Earth observations to assess Oklahoma groundwater storage trends, focusing on seven unconfined or partially unconfined aquifers with a focus on the KCA Territory. Groundwater storage anomalies were computed from downscaled Gravity Recovery and Climate Experiment (GRACE) derived data, which were compared with USGS modular flow (MODFLOW) model outputs and validated using USGS in situ well data. The results revealed a significant decline in groundwater storage from 2004 to 2024 in the western-central part of the state. Strong aquifer-level correlations ($r > 0.70$) were observed between downscaled GRACE and MODFLOW data, with the highest correlation ($r = 0.91$) observed at the largest aquifer. A moderate correlation ($r = 0.41$) was present between GRACE-derived data and well measurements, with discrepancies likely stemming from irregular temporal intervals and uncertainty in specific yield estimates. Our findings support the use of GRACE-based data in groundwater monitoring, which can help partners make informed decisions on sustainable water management for their communities.

Key Terms: drought, GLDAS, NASA Earth observations, aquifer, KCA

Advisors: Dr. Joel Lisonbee (NOAA, CIRES, National Integrated Drought Information System), Dr. Matthew Rodell (NASA Goddard Space Flight Center), Dr. Bailing Li (ESSIC University of Maryland, NASA Goddard Space Flight Center), Dr. Kenton Ross (NASA DEVELOP National Program)

Lead: Tallis Monteiro (North Carolina – NCEI)

1. Introduction

1.1 Background Information

Groundwater, stored in vast networks of underground aquifers, sustains the livelihoods of over 170 million Americans by supplying reliable drinking water and supporting household activities such as cooking and bathing (Environmental Protection Agency, 2024). National industries are also dependent on groundwater resources. The agricultural sector, which contributes to 10.4% of US employment and upholds international supply chains (United States Geological Survey, n.d.), leans on groundwater for 42% of its irrigative needs (Martin, 2025). However, extreme drought conditions over the past two decades have severely impacted aquifer health (Drought.gov, 2025a). Low precipitation levels and high evaporation rates have significantly reduced groundwater recharge, while declining surface water supplies simultaneously increase dependency on underground reserves (USGS Water Science School, 2018).

A state especially affected by groundwater shortages is Oklahoma. The 2010 - 2015 Southern Plains drought spurred extensive crop failure and municipal water scarcity that left millions of Oklahoma residents vulnerable. These conditions resurfaced in 2020 and continue to this day (Drought.gov, 2025b). Drought is particularly devastating for the numerous Tribal Nations whose histories, cultures, and identities revolve around the land and its resources. By advancing sustainable water management, the Kiowa Tribe of Southwest Oklahoma's Kiowa-Comanche-Apache (KCA) Territory plans to uphold the resource as a communal, environmental, and spiritual necessity. Such efforts will also stabilize local economies via farmland irrigation, secure the health of groundwater-reliant civilians, and prioritize Tribal sovereignty over their territory. Federal agencies, like the US Geological Survey's (USGS) Oklahoma-Texas Water Science Center, cooperate with the Kiowa Tribe in this endeavor and are exploring efficient and accurate ways to monitor water budgets. As partners for this study, analyzing groundwater storage and associated anomalies through a remote sensing avenue can offer critical insight for them and other stakeholders in Oklahoma seeking to protect their water resources.

1.2 Scientific Basis

There are many networks of wells used to measure groundwater levels in the US. However, ground-based methods tend to have limited spatial coverage and inconsistent temporal records, making them difficult to utilize for groundwater storage assessment. The integration of NASA's Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions into remote sensing products like the Global Land Data Assimilation System Version 2.2 (GLDAS 2.2) enables large-scale global monitoring of groundwater changes from space (Li et al., 2019). Previous studies have shown that GRACE assimilation into GLDAS 2.2 (GRACE-DA) can improve groundwater simulation in diverse hydrogeological settings and produce strong correlations with ground-based measurements (Guardiola-Albert et al., 2024; Rateb et al. 2020). GRACE-DA has shown significant enhancements in simulating groundwater in areas with high interannual variability in precipitation and can provide a physical indication of the depth and duration of meteorological droughts (Li et al., 2019). As a result, GRACE can provide a more complete picture of how groundwater storage changes over time for our project partners.

1.3 Project Partners & Objectives

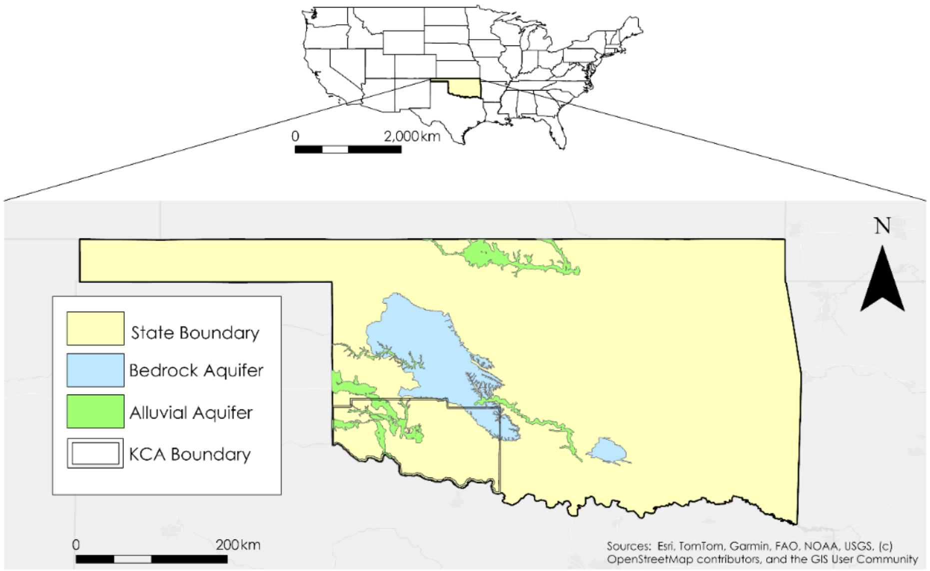
Both project partners are concerned about water scarcity in the state, making it a focal point of their daily work. For example, the Kiowa Tribe Natural Resource Department's mission is to provide current and future Tribal members access to clean air, pure water, and healthy vegetation (Kiowa Tribe, n.d.). The USGS Oklahoma-Texas Water Science Center provides water data and information for collaborators such as the Kiowa Tribe. The Tribe is working to manage, allocate, and plan for the availability of water resources with assistance from USGS to measure these resources and provide water budget analyses. However, the ability to conduct long-term stewardship is challenging due to limited spatiotemporal data of groundwater storage trends in Oklahoma. Analyzing groundwater storage and corresponding anomalies can offer critical insight on groundwater storage trends, drought patterns, and areas of concern. This is especially helpful for the Kiowa Tribe, who prioritizes Tribal sovereignty and seeks to understand historic and current groundwater trends as they work to establish Federal reserved water rights. This project aimed to provide project partners with insights into the feasibility of deriving groundwater trends from Earth observations to help them make informed decisions regarding long-term sustainable water management.

To analyze these groundwater trends, this project utilized GLDAS 2.2 data and USGS modular flow (MODFLOW) models. Our main objectives were to evaluate groundwater storage changes via GLDAS 2.2 Earth observations, calculate anomalies (departures from long-term monthly means) in groundwater storage changes, compare GLDAS 2.2 results with USGS MODFLOW trends, and validate GLDAS 2.2 with USGS National Water Information System (NWIS) in situ well data. Results included temporal time series, spatial maps, and scatter plots of groundwater storage trend analyses. The goal of this feasibility study was to support our partners in understanding the landscape of groundwater storage in Oklahoma and how NASA Earth observations can assist their pursuits.

1.4 Study Area & Study Period

The main study area was the state of Oklahoma, located in the southcentral region of the United States. The study area encompasses unconfined alluvial and mostly unconfined bedrock aquifers across Oklahoma, with the southwestern KCA Territory as a key subset. The selected aquifers include the Salt Fork of the Arkansas River, Washita 1, Rush Springs, Washita 3-4, Arbuckle-Simpson, North Fork Red River and Salt Fork Red River (Figure 1). We used the availability of completed USGS MODFLOW groundwater models to guide the selection of these aquifers for our analysis.

Our study period spans from 2004 to 2024, corresponding with the availability of both GRACE and GLDAS 2.2 datasets and USGS MODFLOW groundwater models. This temporal range allows for historical data analysis, trend comparison, and the validation of GRACE datasets and USGS MODFLOW models. Additionally, the study period captures the most recent extreme event – a drought that occurred between 2010 and 2015 – to enhance the comprehensive analysis of temporally variable groundwater storage.



Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, (c) OpenStreetMap contributors, and the GIS User Community

Figure 1: Map of the study area showing the Oklahoma state boundary, KCA Territory boundary, and the distribution of alluvial and bedrock aquifers.

2. Methodology

We generated trend maps of groundwater storage anomalies, time series of cumulative groundwater storage change anomalies, and a scatter plot for correlation analysis by integrating GRACE Earth observation satellites, hydrological models, and in situ well data. We accomplished this by analyzing three main datasets:

(1) GLDAS 2.2 (2004 - 2024) to obtain a groundwater storage time series from NASA GRACE missions; (2) USGS MODFLOW models to calculate groundwater storage across seven aquifers within our study area to compare with GLDAS 2.2 trends; and (3) USGS National Water Information System (NWIS) well data to validate GLDAS 2.2 groundwater storage change data (Table 1).

Table 1
List of datasets utilized for this project.

Platform/Sensor	**Acquisition Dates**	**Bands/Parameter**	**Spatial Resolution**	**Project Use**
GLDAS 2.2 (GRACE-DA) L4	2004 to 2024	GWS_tavg: daily groundwater storage	25 x 25 km	To calculate groundwater storage trends
USGS MODFLOW-NWT	Varies per model	IN & OUT: monthly groundwater storage	Varies per model	To calculate groundwater storage & compare with GLDAS 2.2 trends
USGS NWIS Database	2004 to 2024	lev_va: daily depth to water levels	N/A	To validate GLDAS 2.2 groundwater storage with site-specific measurements

2.1 Data Acquisition

We derived data on groundwater storage from GLDAS 2.2, which is based on the NASA GRACE and NASA GRACE-FO missions. These joint satellite missions measure variations in Earth's gravity field caused by mass movements of water, allowing for the measurement of terrestrial water storage values (Landerer et al., 2020). We accessed GLDAS 2.2 data from the NASA Goddard Earth Sciences Data and Information Services Center Earthdata portal (Li et al., 2020). The Level 4 GLDAS 2.2 dataset assimilates GRACE-derived terrestrial water storage (TWS) observations into NASA's Catchment Land Surface Model (CLSM) to obtain estimates of TWS components such as soil moisture, groundwater storage and snow water equivalent (Rui et al., 2019). Groundwater storage anomalies are obtained by subtracting monthly groundwater storage estimates by the long-term mean for that month at each grid cell of GLDAS 2.2. We chose a study period of 2004 - 2024 to incorporate the full range of GRACE data available (such that points populate entire calendar years) and downloaded daily unfiltered GLDAS 2.2 data in NetCDF format at a gridded 25 x 25 km spatial resolution. We selected the groundwater storage band (GWS_tavg) to calculate groundwater storage anomalies and annual changes.

To compare cumulative groundwater storage change anomalies from GLDAS 2.2, we acquired MODFLOW model water budget list files for study area aquifers by accessing spatial datasets on the USGS Water Mission Area National Spatial Data Infrastructure (NSDI) data portal, filtering by key words such as "Oklahoma" and "MODFLOW" (USGS National Spatial Data Infrastructure, n.d.). Some MODFLOW models were not available in the database and were instead accessed via published USGS reports (Table 2).

Table 2

Links to MODFLOW data

Aquifer	**Report Reference**	**Data**
Arbuckle-Simpson	Christenson et al. (2011)	https://ok.water.usgs.gov/scripts/sir2011-5029.zip*
North Fork of Red River	Smith et al. (2017)	DOI: 10.5066/F7JQ0ZXH
Rush Springs	Ellis (2018)	DOI: 10.5066/F7Q52NXK
Salt Fork of Arkansas	Gammill & Smith (2025)	DOI: 10.5066/P1KASBTM
Salt Fork of Red River	Smith et al. (2021)	DOI: 10.5066/P927IAO1
Washita 1	Ellis et al. (2020)	DOI: 10.5066/P9PKMG6U
Washita 3-4	Rogers et al. (2023)	DOI: 10.5066/P9UET694

*This link leads to a folder with important metadata on the Arbuckle-Simpson model. However, it does not contain the water budget list file, which our USGS partners provided at a later time (Table A1).

Lastly, we acquired in situ well data to validate GLDAS 2.2 groundwater storage trends from the USGS NWIS portal's "USGS Groundwater Data for Oklahoma" page (USGS National Water Information System, n.d.). Raw data was obtained by selecting "Field Measurements," "County" under "Site Location," then all counties as site-selection criteria. We chose "Display Summary of Selected Sites" to procure site coordinates (for point-to-pixel comparison with GLDAS 2.2) and "Retrieve Groundwater level data for Selected Sites" to attain site-specific water table depth values (lev_va), from which we extracted groundwater storage.

2.2 Data Processing

We processed GLDAS 2.2 NetCDF files using RStudio versions 2024.04.2+764 and 2025.05.0+496 and Esri ArcGIS Pro 3.5.2. First, using RStudio, we aggregated the data across the 2004 to 2024 study period. This aggregation consisted of extracting daily groundwater storage estimates, masking to the Oklahoma state boundary, and aggregating Oklahoma daily values to a monthly scale. Groundwater storage anomalies (GWSA) were subsequently retrieved by subtracting monthly values by the long-term mean for that month, removing seasonality and exposing underlying trends. Annual groundwater storage changes were separately mapped for partner end use (Figure B1).

Using Visual Studio Code 1.102.0, we developed a Python script to read and process the water budget list files used for MODFLOW models. To retrieve cumulative groundwater storage changes on a monthly basis, we compiled and subtracted cumulative inflow values from cumulative outflow values provided in the storage component of water budgets. MODFLOW convention represents inflows as total water released from storage and outflows as total water entering storage since the model's start date (United States Geological Survey, 2017). Changes were then referenced to January 2004 to parallel GLDAS 2.2's time period. We also converted volumetric units (in either cubic meters or cubic feet) to linear units (in millimeters) to match GLDAS 2.2 estimates, dividing MODFLOW values by the area of their respective aquifer as listed in the model package. To facilitate comparison, we derived GLDAS 2.2 groundwater storage changes for each aquifer by subtracting monthly groundwater storage estimates by the value for January 2004. We then subsetted the data to align the two datasets' temporal records. Long-term means were subtracted from the refined datasets to obtain anomalies in cumulative groundwater storage changes.

The team also used in situ well data to validate GLDAS 2.2 groundwater storage measurements. For ease of comparison, we elected to correlate annual groundwater storage changes between the two datasets. We selected wells that fell within the boundary of modeled aquifers with a minimum of 8-months between the first and last measurements of each year. Since the wells had sparse temporal records, we selected a minimum period of 8 months to create a sizeable dataset that still covers most of the calendar year. We then converted depth-to-water-level measurements to changes in water table thickness by subtracting the last available daily value from the first available daily value, as an increase in depth aligns with a decrease in water table height. The team converted thickness to storage estimates by multiplying well data by the specific yield coefficient (Sy) associated with the aquifer in which they were located, derived from MODFLOW data releases (Table 3). We used the same first and last dates for GLDAS 2.2 data, which is already formatted in groundwater storage estimates, to maintain consistency in annual change calculations. We generated the Pearson correlation coefficient to quantify the strength of the relationship between the data points.

Table 3
Specific yield coefficients used to calibrate USGS well data.

Aquifer	Specific Yield Coefficient
Arbuckle-Simpson	0.00926
North Fork of Red River	0.12000
Rush Springs	0.07000
Salt Fork of Arkansas	0.10000
Salt Fork of Red River	0.11820
Washita 1	0.12000
Washita 3-4	0.10220

2.3 Data Analysis

We assessed long-term change patterns in GLDAS 2.2 groundwater storage anomalies by conducting a statewide trend analysis using the Mann-Kendall test and Sen's slope estimator. The Mann-Kendall method is a non-parametric test for detecting significant trends in time series and is widely used to detect trends in hydrological data (Hamed, 2008). The Sen's slope technique is used with the Mann-Kendall test to quantify the weight of significant trends (Berhanu et al., 2024). We ran the Mann-Kendall test and Sen's Slope method on monthly groundwater storage anomalies via the "trend" package in RStudio, producing a gridded trend map. The map correlates Sen's slope values to pixel color on a base raster, with points overlayed to indicate the presence of significant trends as determined by Mann-Kendall p-values < 0.05.

The team also generated time series representing anomalies in cumulative groundwater storage changes that compared MODFLOW trends against GLDAS 2.2 trends. CSVs of processed MODFLOW data were uploaded into RStudio and plotted alongside respective GLDAS 2.2 datasets. For the validation step, we plotted in situ well and GLDAS 2.2-derived groundwater storage changes on a scatterplot to visualize the correlation.

3. Results

3.1 Analysis of Results

The Sen's slope trend map, featuring GLDAS 2.2 data, shows the rate of change of groundwater storage anomalies across the 20-year study period (Figure 2). The strength and directionality of trends reveal strong distinctions in groundwater storage behavior between Oklahoma's subregions. Negative slopes begin at a longitude of approximately –97° and continues westward, with the westernmost portion of the state possessing the most potent negative trends. Nearly all aquifers of interest overlap with potentially water-stressed regions, particularly Salt Fork Red River, North Fork Red River, and Rush Springs. These three aquifers also intersect the KCA Territory. Statistically significant trends established by the Mann-Kendall test are present in almost every locality except for central-eastern Oklahoma, where parts of Arbuckle-Simpson and Washita River 3-4 reside.

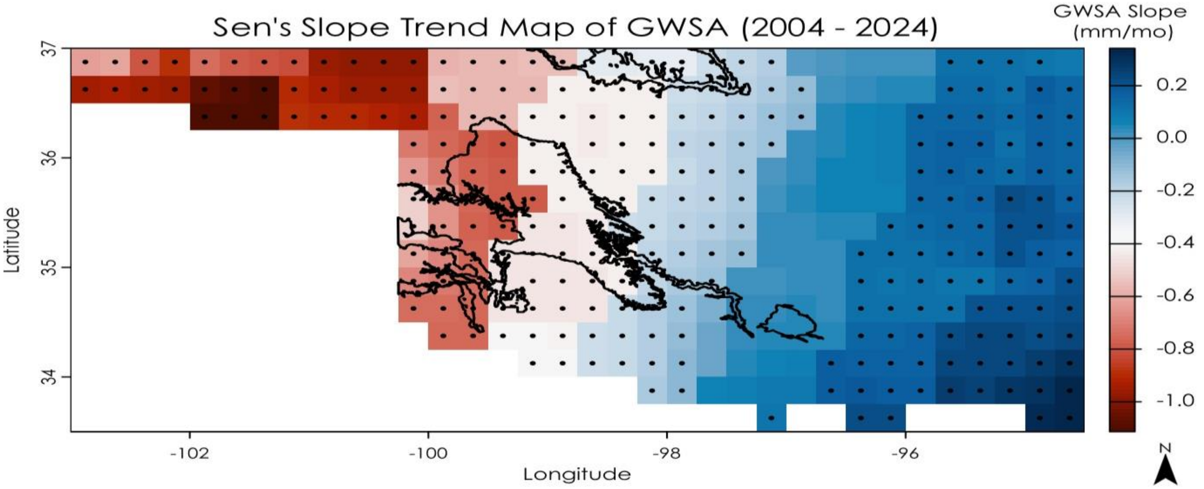


Figure 2. Trend map exhibiting Sen's slope values (in millimeters per month) for GLDAS 2.2 groundwater storage anomaly time series. Points are overlayed on pixels with significant trends as determined by Mann-Kendall p-values. Aquifer boundaries are delineated.

We created time series of MODFLOW and GLDAS 2.2 anomalies in cumulative groundwater storage changes starting January 2004, each corresponding to a study area aquifer. Monthly anomalies summarized over the Salt Fork Arkansas River watershed are shown as an example in Figure 3 and monthly anomaly time plots of all watersheds are available in in Appendix B (Figures B1 – B7). We generated correlation coefficients (r) to assess the strength of the relationship between the two datasets and found that all aquifers exhibited strong correlations of > 0.7. Several aquifers displayed strong negative trends (Table C1). A time series of annual GLDAS 2.2 anomalies across the State of Oklahoma from 2004 to 2024 is captured in Figure C1.

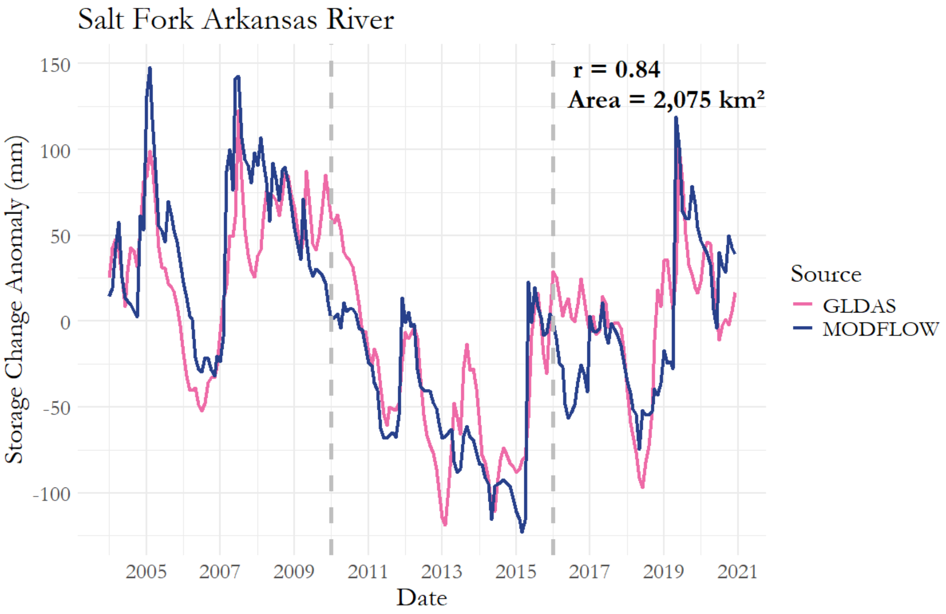


Figure 3. Salt Fork Red River aquifer time series displaying anomalies in monthly cumulative groundwater storage changes in GLDAS 2.2 and MODFLOW data, referenced to January 2004 and running 2004 to 2020. Vertical dashed gray lines signify the 2010 - 2015 Southern Plains drought.

Finally, we generated a scatterplot that quantifies the relationship between in situ well data and GLDAS 2.2 estimates as a validation step (Figure 4). We obtained a correlation coefficient of 0.41, which indicates that there is a moderate correlation between datasets' annual groundwater storage change values.

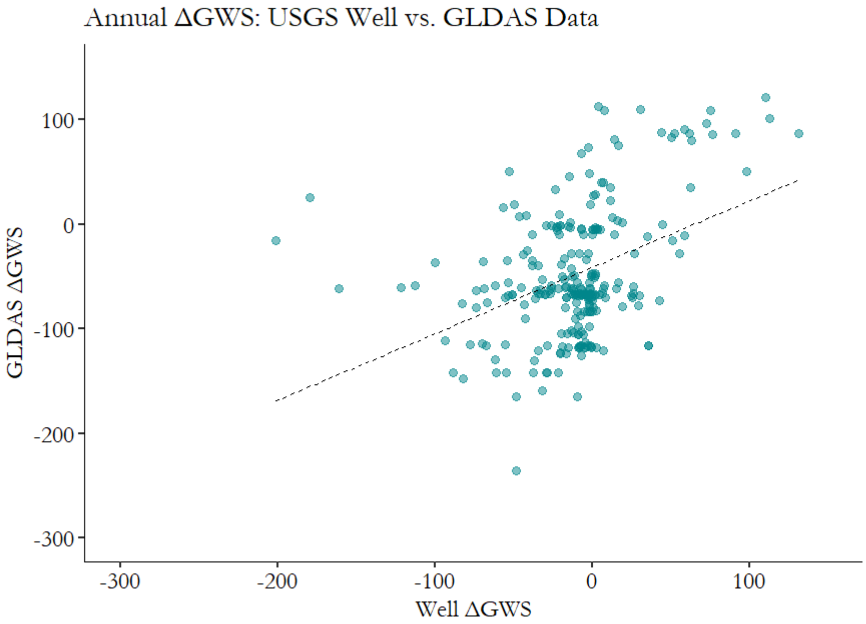


Figure 4. Scatter plot representing the correlation between annual groundwater storage changes from GLDAS 2.2 and USGS NWIS data.

3.2 Errors & Uncertainties

Several limitations are present in these datasets and comparative analyses. For instance, GLDAS 2.2 can effectively simulate shallow subsurface layers but may not be able to model fully confined aquifers due to the limitation of CLSM (Guardiola-Albert et al. 2024). Additionally, as CLSM only simulates natural hydrologic processes, anthropogenic groundwater withdrawals (which are detected by GRACE satellites) may not be fully incorporated into GLDAS 2.2. However, based on Figure 3, the lack of simulation of groundwater withdrawals in CLSM did not negatively impact groundwater estimates.

The scope of our analysis was also hindered by the MODFLOW model's limited spatial coverage, resulting in aquifer-level comparisons rather than statewide. MODFLOW also utilizes approximation factors such as grid cells and boundary conditions. This can smooth estimates or give rise to unnatural peaks or pits. When plotting the two datasets against each other, we had to navigate different temporal resolutions by cutting the GLDAS record to match the length of MODFLOW models for aquifer time series. Further discrepancies can be attributed to specific yield estimates used in MODFLOW models, which may affect the magnitude of trends.

For the USGS NWIS well data, irregular temporal records of in situ groundwater levels restricted our analysis to an annual basis. Furthermore, a lack of wells with values in both January and December of each year compelled us to include sites with measurements at least eight months apart to capture most of a calendar year. These temporal inconsistencies may have created discrepancies when correlating well data with GLDAS 2.2 values.

4. Conclusions

4.1 Interpretation of Results

Downscaled GRACE data accessed through GLDAS 2.2 can be used to monitor groundwater storage trends across the state of Oklahoma. Our findings showed that there has been a decline in groundwater storage in central and western Oklahoma from 2004 - 2024. The high correlations between the GLDAS 2.2 and MODFLOW time series for individual aquifers throughout the state demonstrate the accuracy of GLDAS 2.2 data and the feasibility of using NASA Earth observations to study groundwater storage trends. Furthermore, we obtained a moderate correlation when validating GLDAS 2.2 trends with in-situ well data, even with the limited availability of consistent well data and the coarse spatial resolution of GLDAS 2.2. These promising results position GRACE and GLDAS as potential workarounds for studying groundwater storage trends in places with limited data resources. The trends calculated in this study may help our partners in identifying areas of high water scarcity risk or serve as a guide for prioritizing the allocation of resources effectively. For example, the statewide trend map can show which existing water resources or aquifers should be monitored closely, where future infrastructure should be placed, or which communities will be the most vulnerable to water scarcity issues.

4.2 Feasibility & Partner Implementation

Though GLDAS 2.2 cannot pinpoint exact locations of aquifer withdrawal or extend deep enough to represent fully confined aquifers, it is a valuable tool in understanding general trends. Our study shows the feasibility of using GLDAS 2.2 to monitor groundwater storage trends across a region like Oklahoma. The results support our partners' knowledge of the region. The visualizations showcasing these results can aid the partners in communicating the issue of groundwater storage decline and help support future decisions pertaining to long-term sustainable water management.

5. Acknowledgements

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6. Glossary

Anomaly – Departure from the long-term mean
Aquifer – Underground layers of rock or sediment that hold and transmit water
Alluvial Aquifer – Shallow unconfined aquifer made of unconsolidated sediment deposited river
Bedrock Aquifer – Groundwater stored solid rock formations which may be unconfined or confined depending on the surrounding geology.
Unconfined Aquifer – an aquifer whose upper water surface (water table) is at atmospheric pressure, and thus can rise and fall (Figure D1)
Confined Aquifer – an aquifer overlain by a low-permeability layer (confining layer) which restrict water movement, under pressure (Figure D1)
CSV – Comma Separated Values, a file type used for tabular data
Downscale – The process of refining large scale data to a finer spatial resolution
Earth Observations – Satellites and sensors that collect information about the Earth's physical, chemical, and biological systems over space and time
GLDAS – Global Land Data Assimilation System
GRACE – Gravity Recovery and Climate Experiment
Groundwater Storage (GWS) – The amount of groundwater stored in an aquifer
GWSA – Groundwater Storage Anomaly
Mann-Kendall Test – A non-parametric test used to assess the trend in a time series
MODFLOW – A numerical groundwater flow modeling software developed by USGS to simulate groundwater conditions
NetCDF – Network Common Data Form, a file format and set of libraries used to store and share array-oriented scientific data
Remote Sensing – Process of detecting and monitoring the physical characteristics of an area from a satellite or aircraft to measure its reflected and emitted radiation from a distance.
Sen's Slope Estimator – A method to quantify the magnitude of a trend in a time series
Specific Yield – The volume of water that a unit volume of saturated rock, soil, or an aquifer will release or drain from storage due to gravity
Temporal – Movement or sequence of data over time

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8. Appendices

Appendix A: MODFLOW Files

Table A1.

List File for Arbuckle-Simpson MODFLOW Model

Aquifer	List File
Arbuckle-Simpson	https://drive.google.com/file/d/1qdPLwNb_Kd_h3oY81KQEQaObhJ4UdChQ/view?usp=drive_link

Appendix B: Anomalies in Monthly Cumulative Groundwater Storage in GLDAS 2.2 and MODFLOW

Aquifer time series displaying anomalies in monthly cumulative groundwater storage changes in GLDAS 2.2 and MODFLOW data, referenced to January 2004. Vertical dashed gray lines signify the 2010 - 2015 Southern Plains drought. Each graph has a different end date and reference period due to MODFLOW availability.

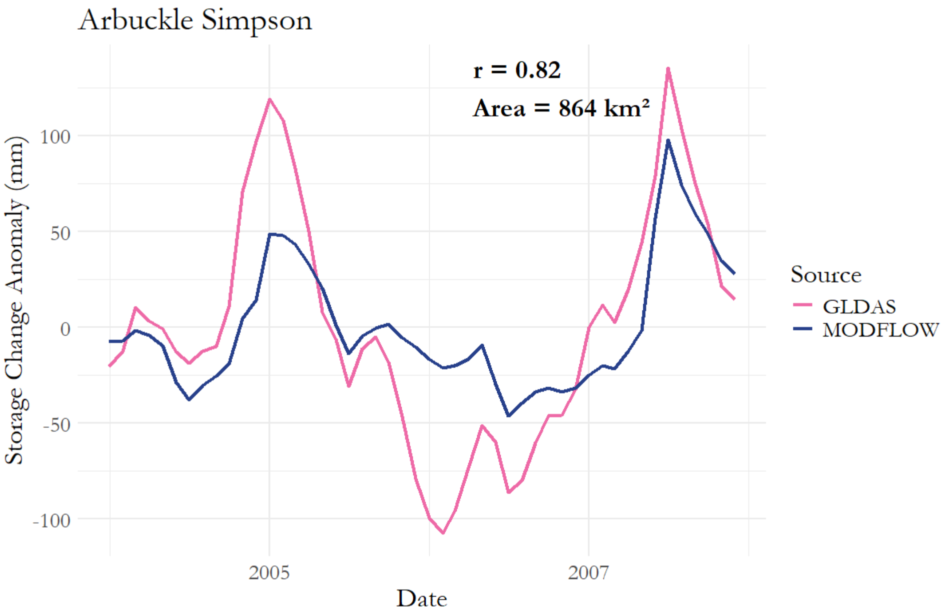

Figure B1. Arbuckle Simpson Watershed 2004 - 2007.

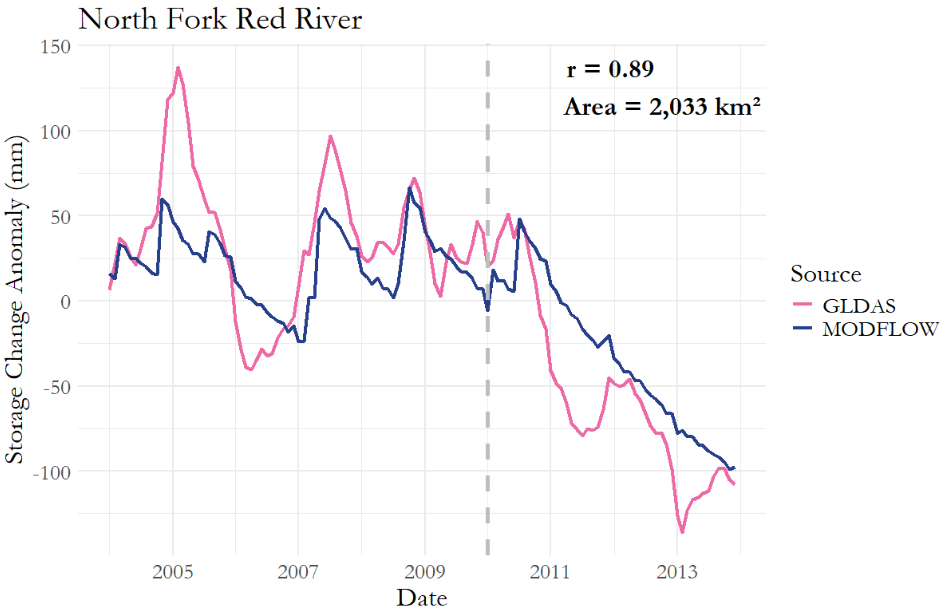

Figure B2. North Fork Red River Watershed 2004 - 2013.

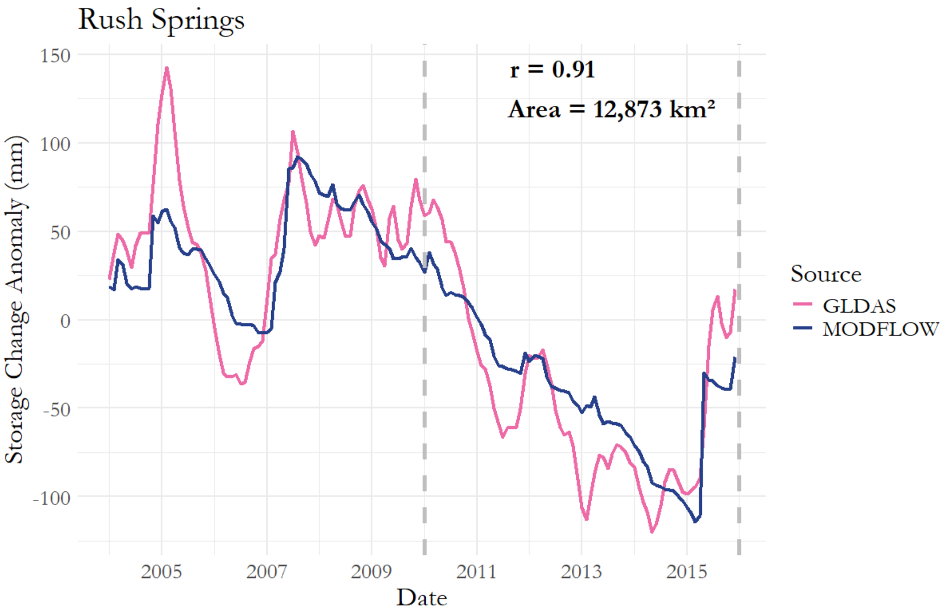

Figure B3. Rush Springs Watershed 2004 - 2015.

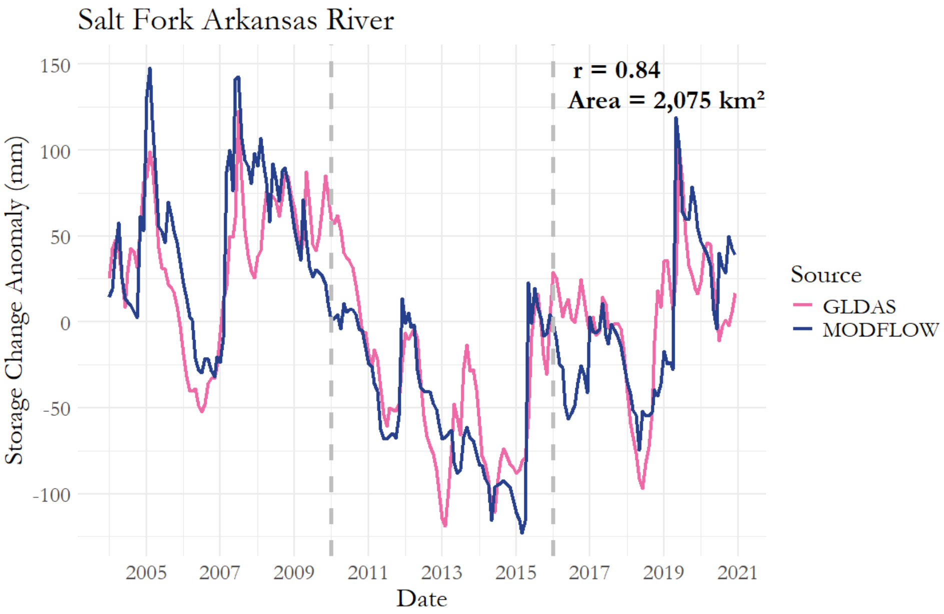

Figure B4. Salt Fork Arkansas River Watershed 2004 - 2020.

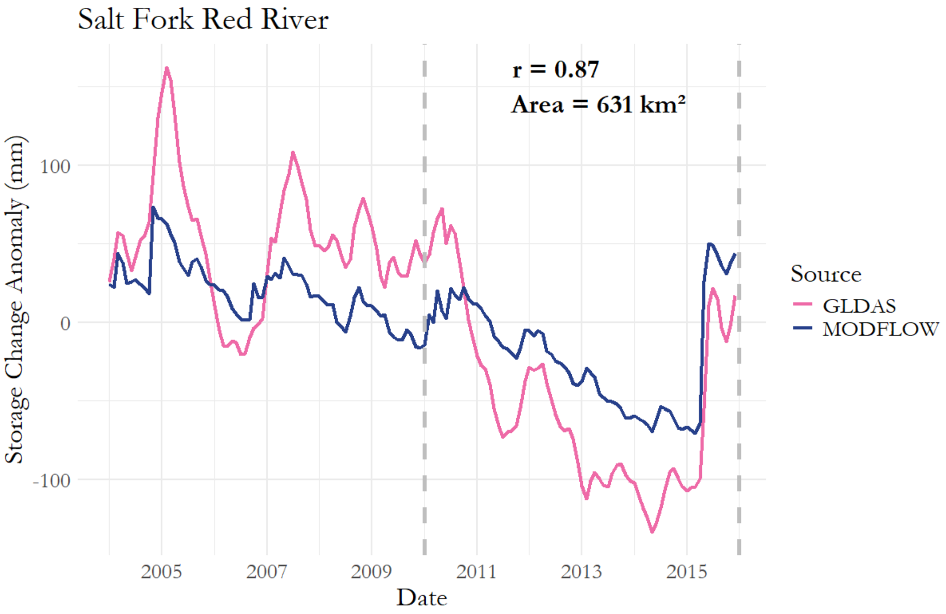

Figure B5. Salt Fork Red River Watershed 2004 - 2015.

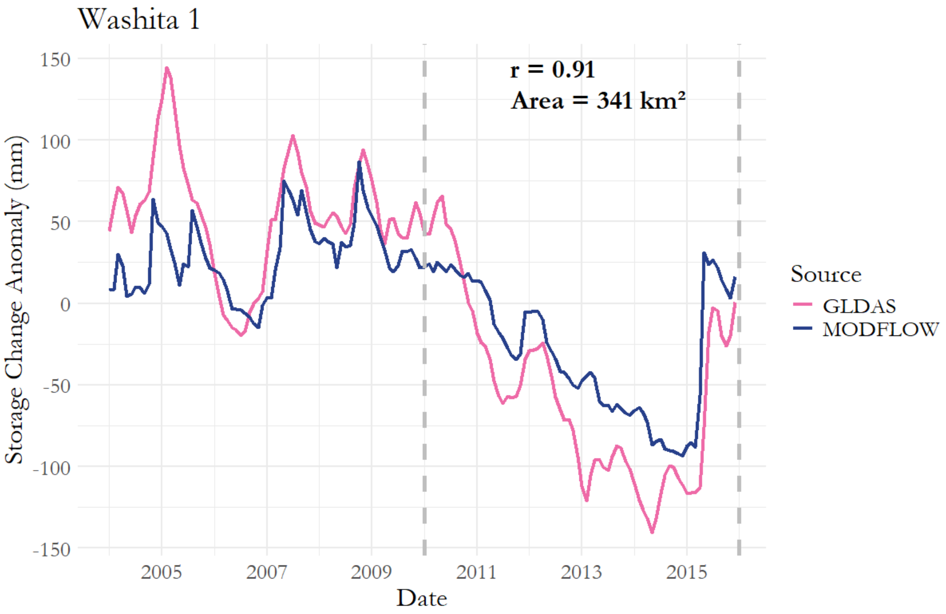

Figure B6. Washita 1 Watershed 2004 - 2015.

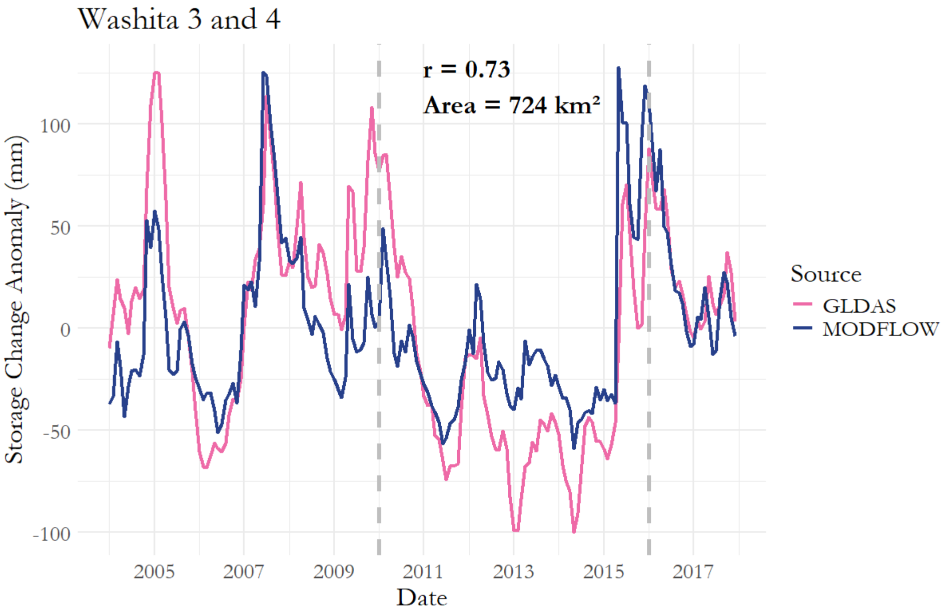

Figure B7. Washita 3 and 4 Watersheds 2004 - 2015.

Appendix C: Annual GLDAS Groundwater Storage Change

Table C1.

Sen's Slope of GLDAS Groundwater Storage Anomalies per Aquifer (2004 - 2024)

Aquifer	**Area (km²)**	**Sen's Slope (mm/year)**
Arbuckle-Simpson	863.64	0.48
North Fork Red River	2033.29	**-6.96**
Rush Springs	12873.12	**-4.80**
Salt Fork Arkansas River	2075.27	**-3.84**
Salt Fork Red River	631.03	**-7.44**
Washita River Reach 1	341.42	**-9.00**
Washita River Reach 3 & 4	724.14	-0.72

**Significant trends (p-value >0.05) bolded*

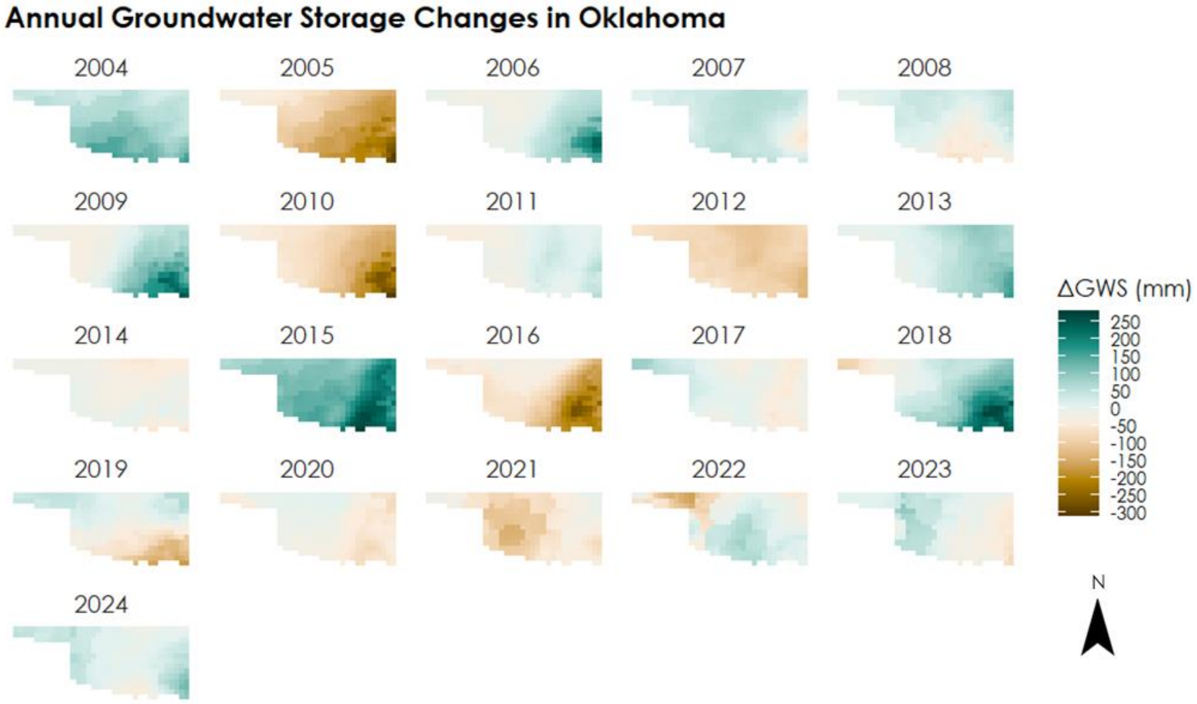

Figure C1. Annual changes in GLDAS 2.2 groundwater storage in Oklahoma for the years 2004 to 2024. Positive changes are shown in blue while negative changes are shown in brown.

Appendix D: Groundwater Dynamics

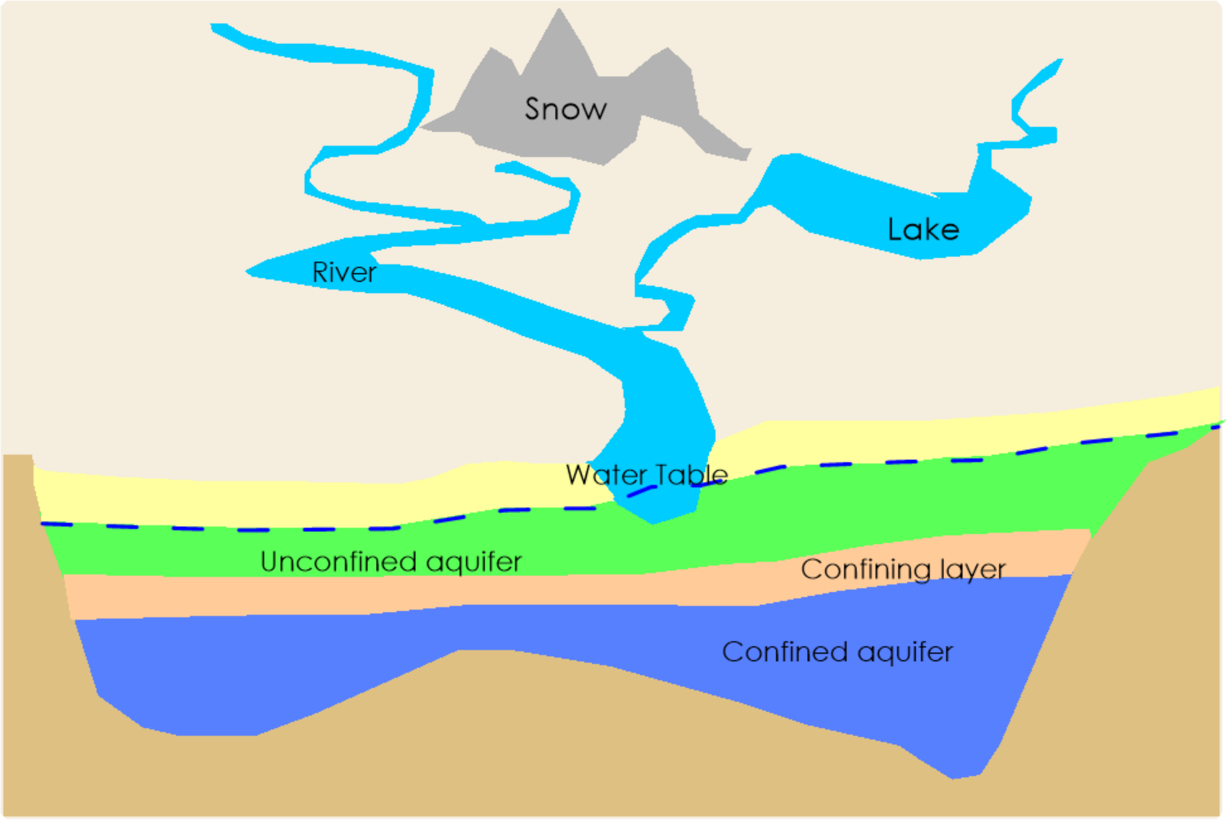

Figure D1. Conceptual diagram of hydrologic systems