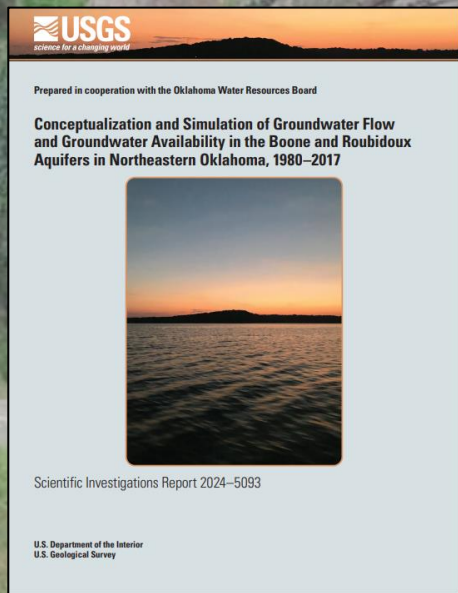


# Conceptualization and Simulation of Groundwater Flow and Groundwater Availability in the Boone and Roubidoux aquifers in Northeastern Oklahoma, 1980–2017

Adam R. Trevisan, Cory A. Russell, Hayden A. Lockmiller, Derrick L. Wagner, Jessica S. Correll, and Katherine J. Knierim



## MODFLOW-NWT model used for the simulation of groundwater flow and analysis of groundwater availability in the Boone and Roubidoux aquifers in northeastern Oklahoma, 1980-2017

### Dates

Publication Date : 2024-09-23  
Start Date : 1980-01-01  
End Date : 2017-12-31

### Citation

Trevisan, A.R., Correll, J.S., and Knierim, K.J., 2024. MODFLOW-NWT model used for the simulation of groundwater flow and analysis of groundwater availability in the Boone and Roubidoux aquifers in northeastern Oklahoma, 1980–2017. U.S. Geological Survey data release. <https://doi.org/10.5066/P9KWVUAV>.

### Summary

The U.S. Geological Survey (USGS), in cooperation with the Oklahoma Water Resources Board (OWRB), constructed a finite-difference numerical groundwater-flow model of the Boone and Roubidoux aquifers in northeastern Oklahoma by using MODFLOW-NWT (version 1.1.4) with the Newton formulation solver to simulate groundwater flow and account for the drying and rewetting of cells within the groundwater-flow model. The numerical groundwater-flow model was discretized into four layers consisting of 354 rows by 261 columns with a 2,000-feet by 2,000-feet cell size. The model layers were used to simulate the Western Interior Plains confining system, the Boone aquifer, the Ozark confining unit, and the Roubidoux aquifer. The model was temporally discretized into one steady-state stress period followed by 456 monthly transient stress periods spanning from January 1980 to December 2017. The steady-state stress period typically consisted of mean annual inputs from January 1980 to December 2017, but inputs from 1979 were included for some of the simulations.



Map »

# Purpose

- **Project in cooperation with the Oklahoma Water Resources Board**
- **General questions:**
  1. **How much groundwater is available in the Boone and Roubidoux aquifers?**
  2. **How much groundwater might be available in the future in the Boone and Roubidoux aquifers?**
- **To achieve these goals:**
  - **Conceptual water budget (1980–2017)**
  - **Groundwater-flow model**



# Study Area and Hydrogeologic Units

## Study area

- Nationally referred to as the Ozark Plateaus Aquifer System
- Extends into Kansas, Missouri and Arkansas

### Hydrogeologic Layer

Western Interior Plains Confining Unit

Boone Aquifer

Ozark Confining Unit

Roubidoux Aquifer

St. Francois Confining Unit

St. Francois Aquifer

Basement Rock

Part of  
this study

Increasing Depth



Extent of the Ozark Plateaus Aquifer system  
(Includes the Boone and Roubidoux aquifers; modified from  
Westerman and others, 2016)


# Hydrogeologic Units

## EXPLANATION


Extent of rocks contained in each hydrogeologic unit (Russell and Stivers, 2020a)

 Western Interior Plains confining unit

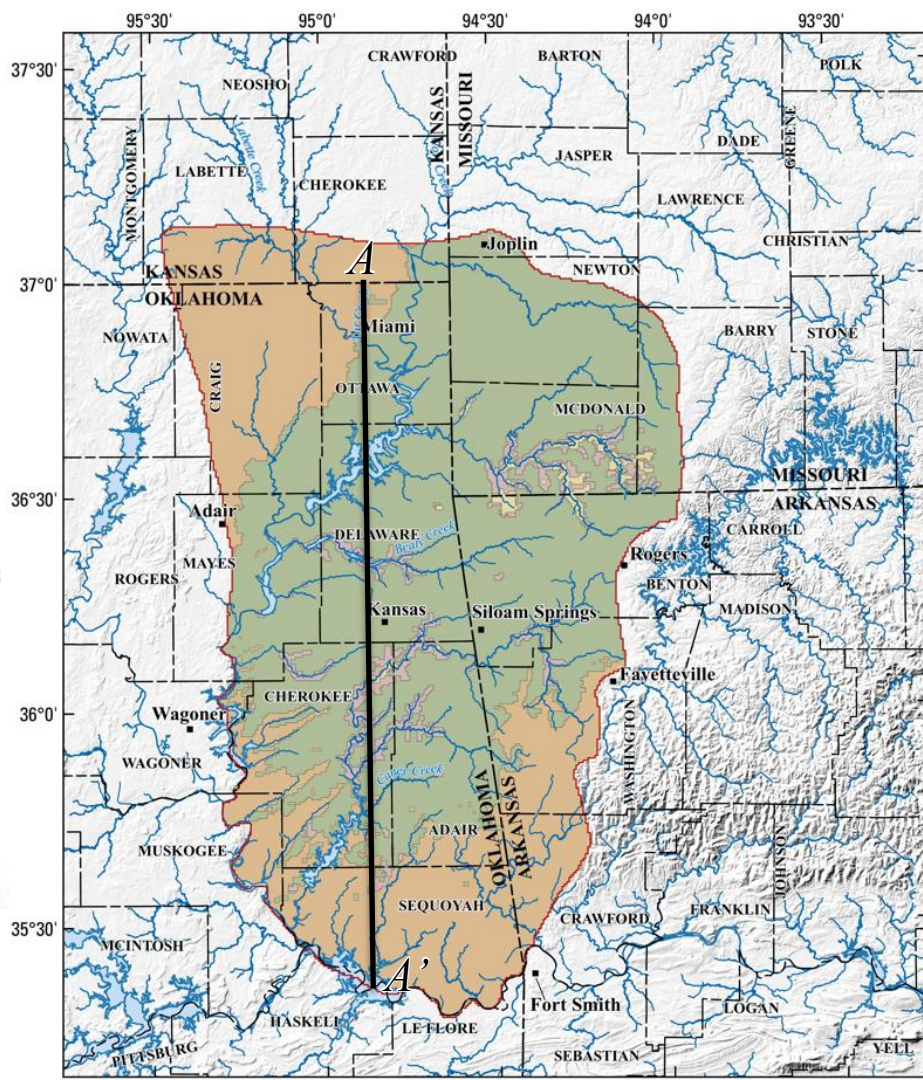
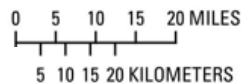
 Boone aquifer

 Ozark confining unit

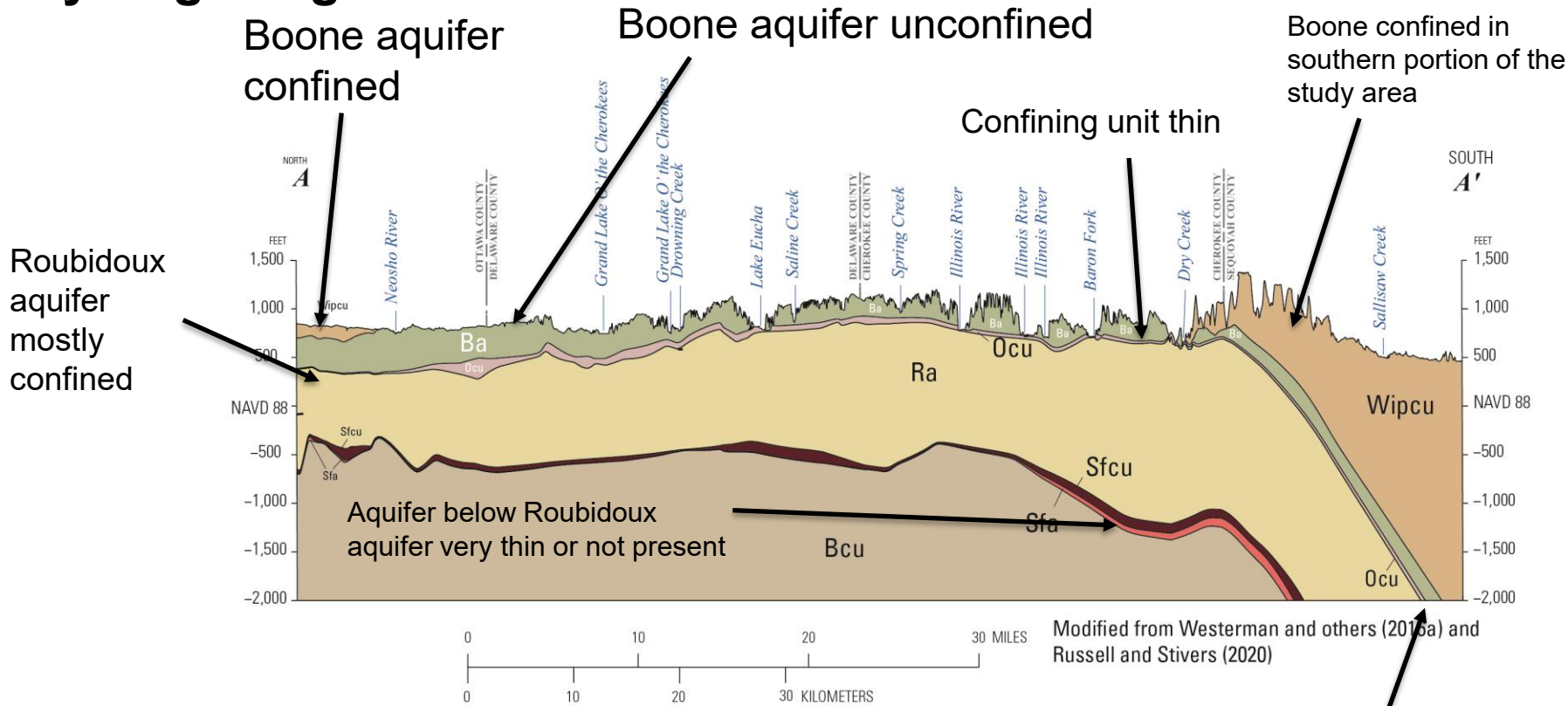
 Roubidoux aquifer

 Study area

 Ozark Plateaus aquifer system (OPAS) boundary (modified from Westerman and others, 2015)



# Hydrogeologic Units



# Hydrogeology

## Boone Aquifer

- Mostly made up of limestone
- Relatively thin
- Does not yield as much as Roubidoux
- Karst prone

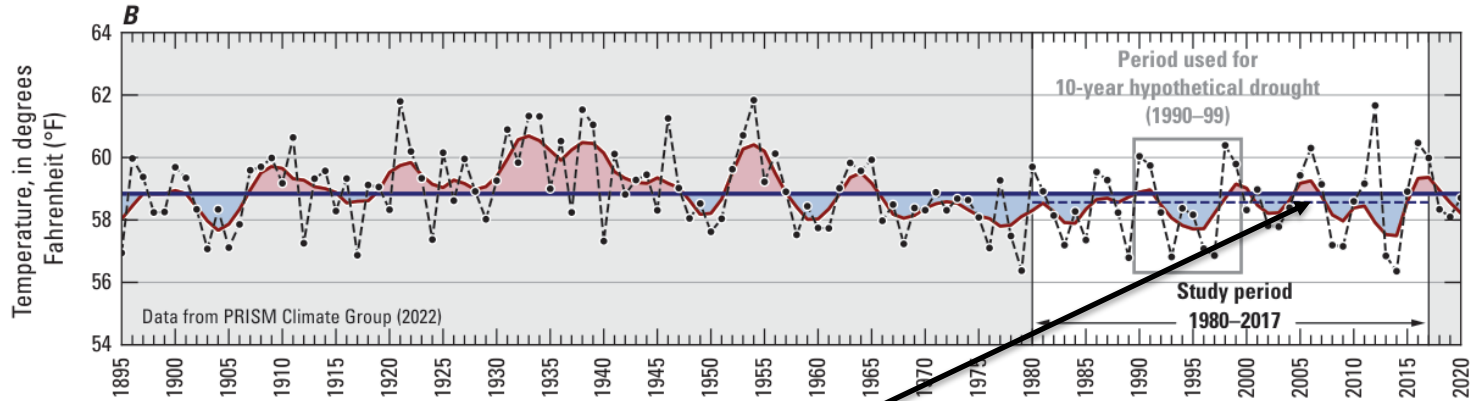
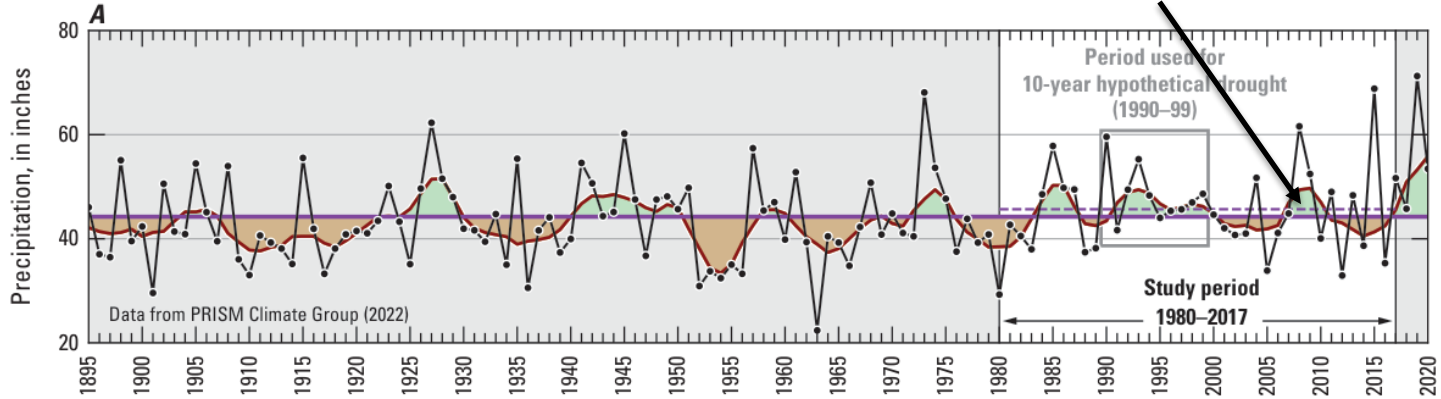
## Roubidoux aquifer

- Mostly made up of limestone and dolostone, also, some sandstones
- Much thicker than the Boone aquifer
- Relatively high yields
- Karst prone

Hydrogeologic unit	Thickness in entire study area, in feet		Thickness in the Oklahoma part of the study area, in feet	
	Mean	Median	Mean	Median
Western Interior Plains confining unit	828	542	895	551
Boone aquifer	241	248	232	238
Ozark confining unit	43	43	47	47
Roubidoux aquifer	1,422	1,300	1,416	1,281

# Long-term Climate

Recently wetter than average

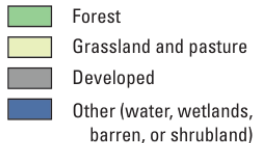


Recently cooler than average

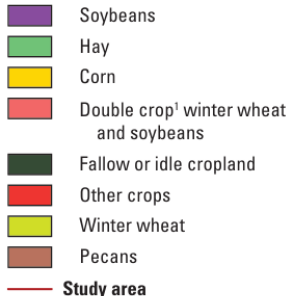
# Land Use

## EXPLANATION

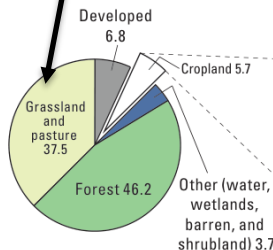
Land-cover type, 2020  
(National Agricultural  
Statistics Service, 2021)



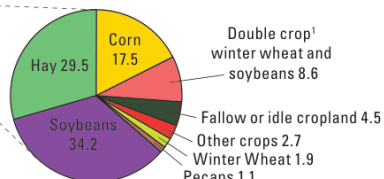
Crop-cover type, 2020  
(National Agricultural  
Statistics Service, 2021)



Mostly  
grassland/pasture and  
forest



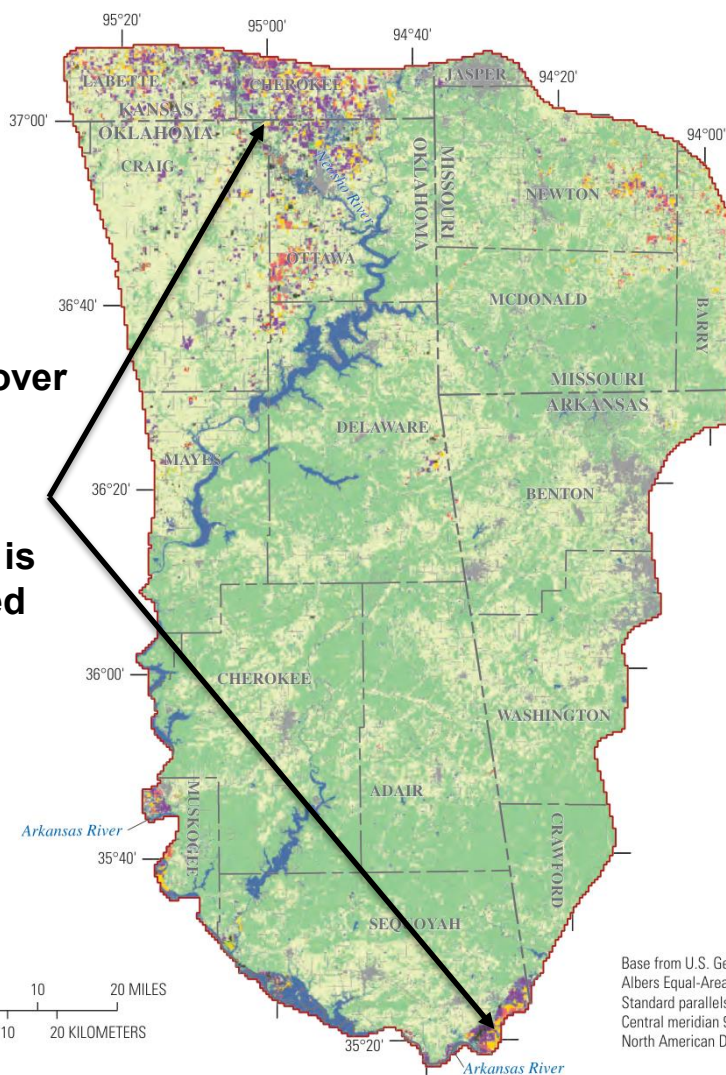
Land-cover type, 2020, in percent  
(National Agricultural Statistics  
Service, 2021)



Crop-cover type, 2020, in percent  
(National Agricultural Statistics  
Service, 2021)

<sup>1</sup>Double crop indicates that multiple crops are grown at different times of the year.  
Percentages may not sum to 100 percent because of rounding differences.

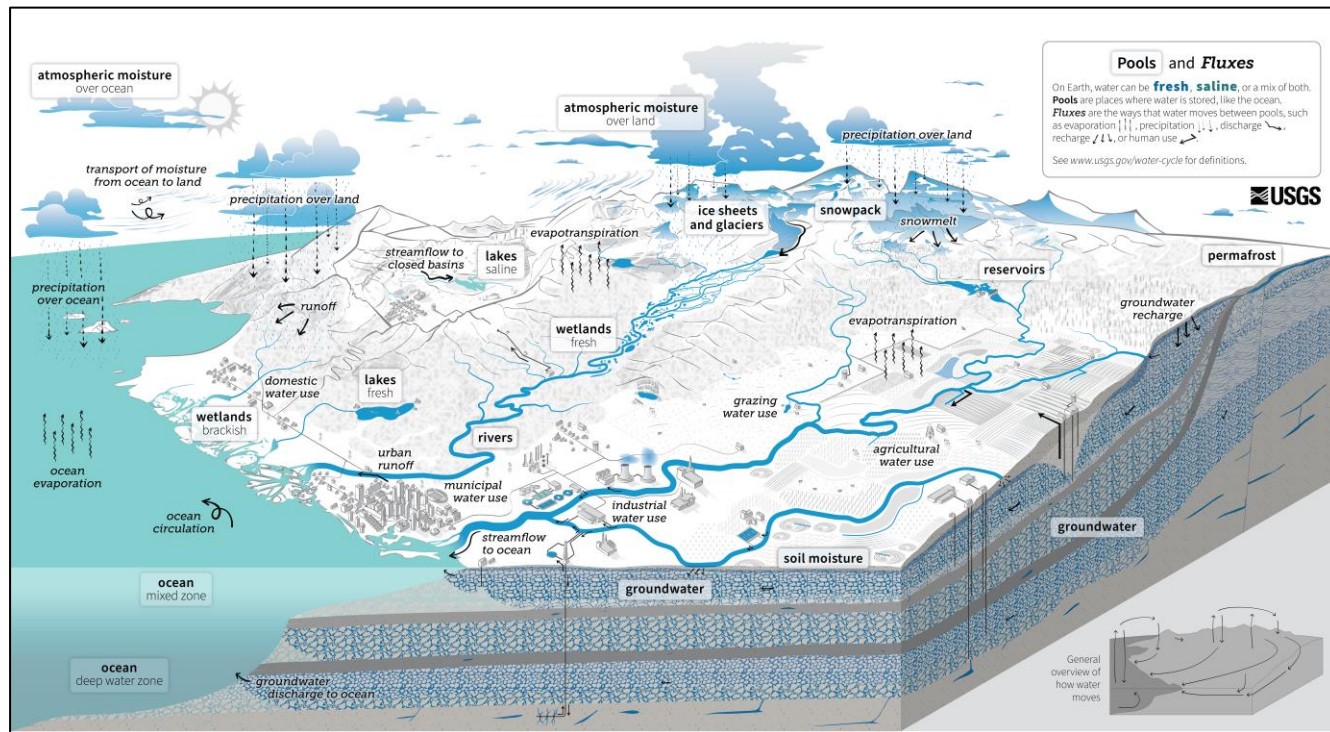
Crop cover  
mostly  
where  
Boone  
aquifer is  
confined



Base from U.S. Geological Survey digital data, various scales  
Albers Equal-Area Conic projection  
Standard parallels 29°30' and 45°30' N.  
Central meridian 96°00' W.  
North American Datum of 1983

# Components of flow to the Boone and Roubidoux aquifers

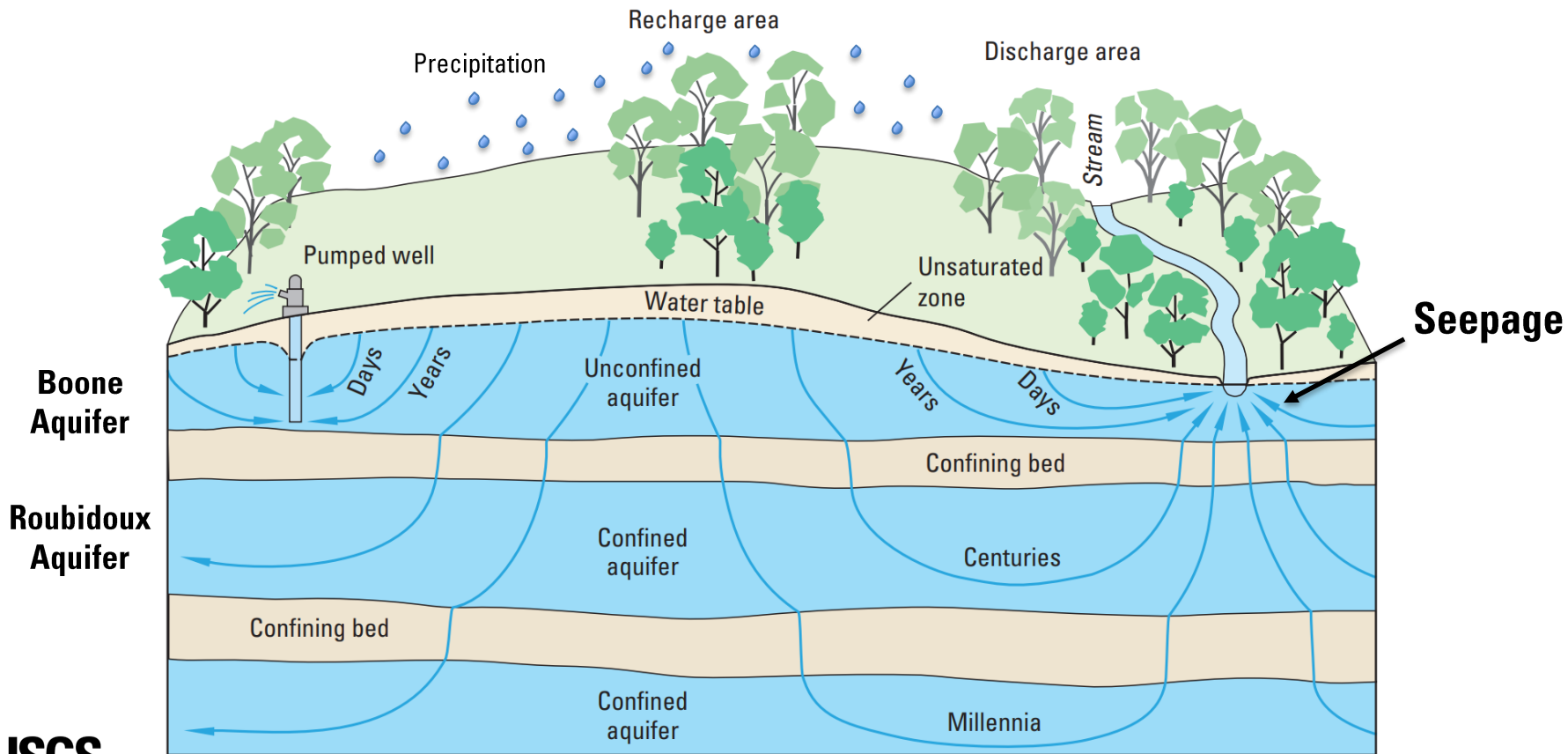
- Many different inflows can contribute water to the aquifer
- The goal is to identify which sources are substantial to the groundwater-flow budget



# Components of flow to the Boone and Roubidoux aquifers

- **Conceptual model is an average flow into and out of the aquifer**
  - **For this report, the study period was 1980–2017**
- **Recharge – net flow of precipitation to the aquifer**
- **Seepage – net flows from streams, lakes, and springs**
- **Groundwater use – reported groundwater use**
- **Flows across boundaries – flows to other parts of the aquifer**
- **Leakage – flows from the Boone to the Roubidoux (or vice versa)**
- **Groundwater storage change – change in the amount of water in the aquifer**

# Recharge

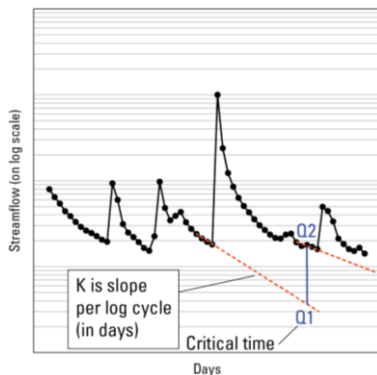


# Recharge — Rorabaugh (RORA) method (Rorabaugh, 1964)

[--, not applicable; Mo., Missouri; Okla., Oklahoma; Ark., Arkansas; Recharge estimated by using the RORA program included in the U.S. Geological Survey (USGS) Groundwater Toolbox (Barlow and others, 2015)]

- **USGS Groundwater Toolbox (USGS, 2018)**
- **Used 16 USGS streamgages**
- **About 10.62 inches annually**
- **Equation:**

$$R = \frac{2 * [Q2 - Q1] * K}{2.3026}$$



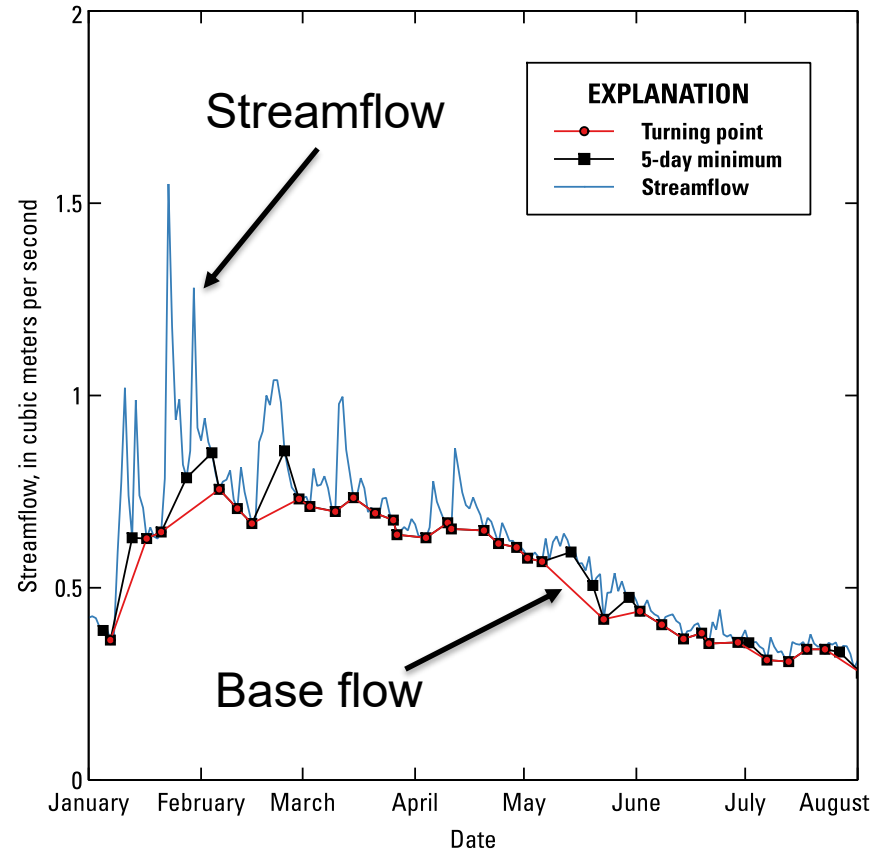
USGS station number	USGS station name	Station short name and map identifier (table 1; fig. 1A)	Period analyzed	Mean annual RORA-program estimated recharge, in inches	Drainage area, in square miles
07187000	Shoal Creek above Joplin, Mo.	9s	1980–2017	12.47	427
07188653	Big Sugar Creek near Powell, Mo.	12s	2002–17	8.48	141
07188838	Little Sugar Creek near Pineville, Mo.	13s	2006–17	10.70	195
07188885	Indian Creek near Lanagan, Mo.	14s	2002–17	10.03	239
07189100	Buffalo Creek at Tiff City, Mo.	16s	2002–17	11.02	60.8
07189540	Cave Springs Branch near South West City, Mo.	17s	1999–2017	7.16	8.00
07189542	Honey Creek near South West City, Mo.	18s	1999–2017	9.65	48.7
071912213	Spavinaw Creek near Colcord, Okla.	23s	2003–17	9.65	163
07191222	Beaty Creek near Jay, Okla.	24s	2000–17	7.52	59.1
07194800	Illinois River at Savoy, Ark.	25s	2003–15	8.13	167
07195000	Osage Creek near Elm Springs, Ark.	27s	1997–2015	14.42	130
07195865	Sager Creek near West Siloam Springs, Okla.	33s	1998–2017	12.74	19.1
07196000	Flint Creek near Kansas, Okla.	34s	1994–2017	10.05	116
07196973	Peacheater Creek at Christie, Okla.	38s	1994–2002	11.40	25.0
07197000	Baron Fork at Eldon, Okla.	39s	1980–2017	10.46	312
07197360	Caney Creek near Barber, Okla.	40s	1999–2017	10.81	90.2
Mean	--	--	--	<sup>1</sup> 10.29 (10.38)	--
Watershed-area-weighted mean	--	--	--	<sup>1</sup> 10.62 (10.14)	--

<sup>1</sup>Mean values for streamgages within Oklahoma are in parentheses.



# Base-flow separation

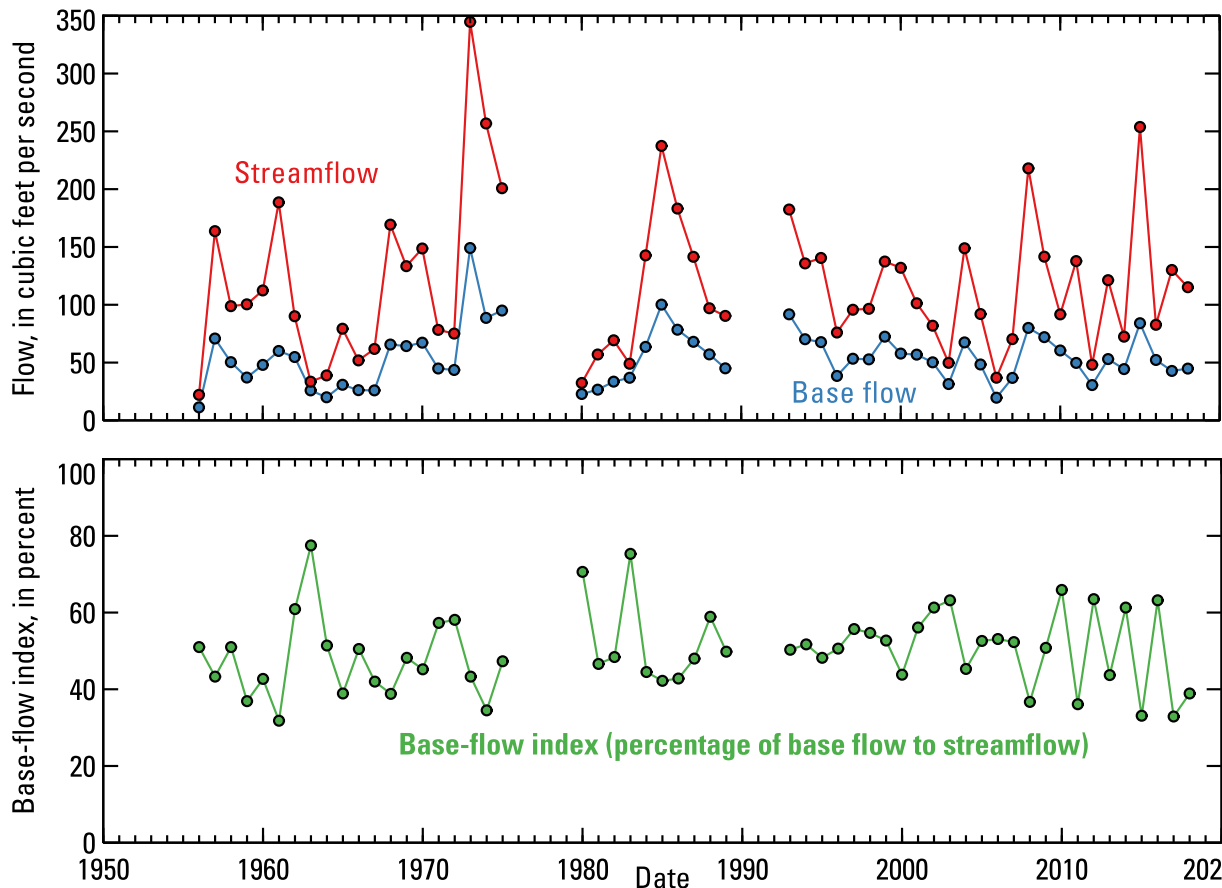
- **Base flow is the component of streamflow from the aquifer**
- **Want to estimate base flow**
  - **Difficult to measure directly**
  - **Commonly estimated by hydrograph methods**  
“Estimated by plotting”
- **We used the base flow index (BFI) method (Wahl and Wahl, 1995) for this project**



Data from Institute of Hydrology, 1980

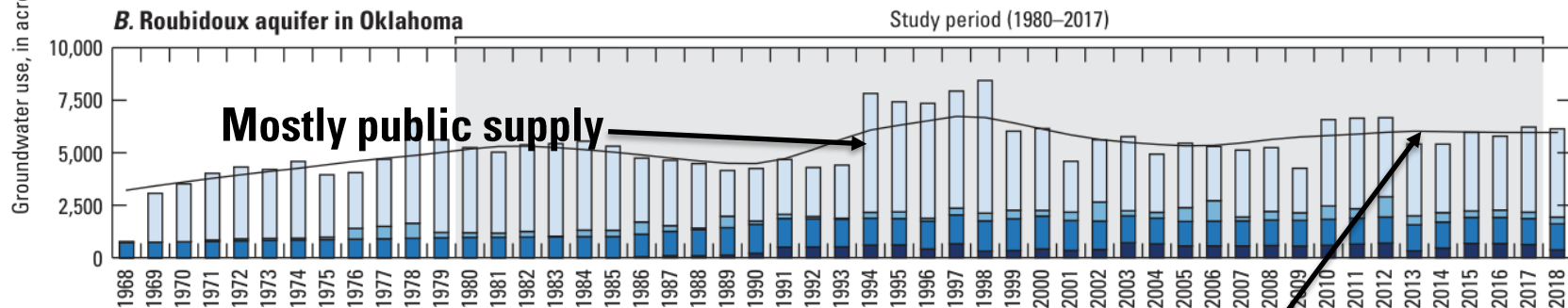
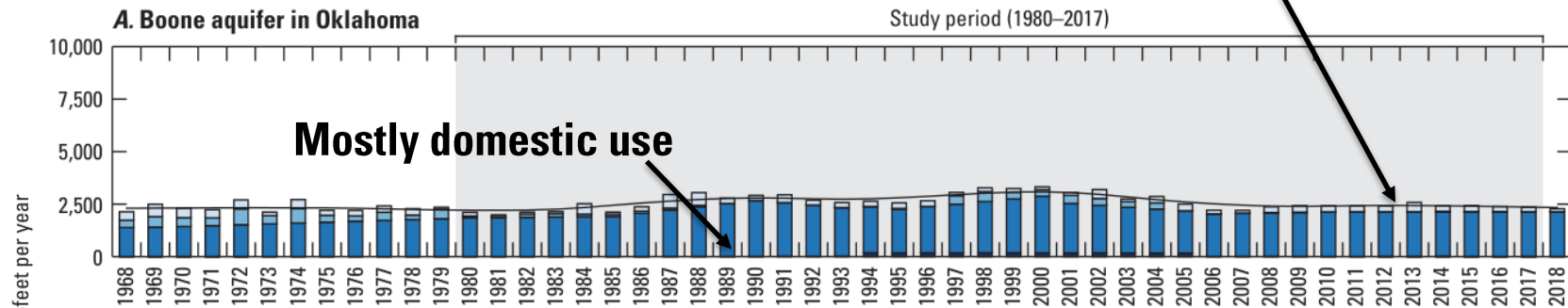
# USGS Streamgauge 07196000 Flint Creek near Kansas, Okla.

- Streamflows and base flows don't show strong downward or upwards patterns
- Annual base flows are about 50 percent of streamflow on average
- This example is like other streams in the area



# Groundwater Use

**Boone groundwater withdrawals mostly the same year-to-year**



## EXPLANATION

- Groundwater-use type
- Agriculture
  - Domestic
  - Other
  - Public supply
- LOWESS curve,<sup>1</sup> total groundwater use

**Roubidoux groundwater withdrawals mostly the same year-to-year. More fluctuation than Boone.**

<sup>1</sup>A LOWESS curve is a locally weighted scatterplot smoothing curve (Cleveland, 1979). A smoothing factor of 0.25 was used for these plots.

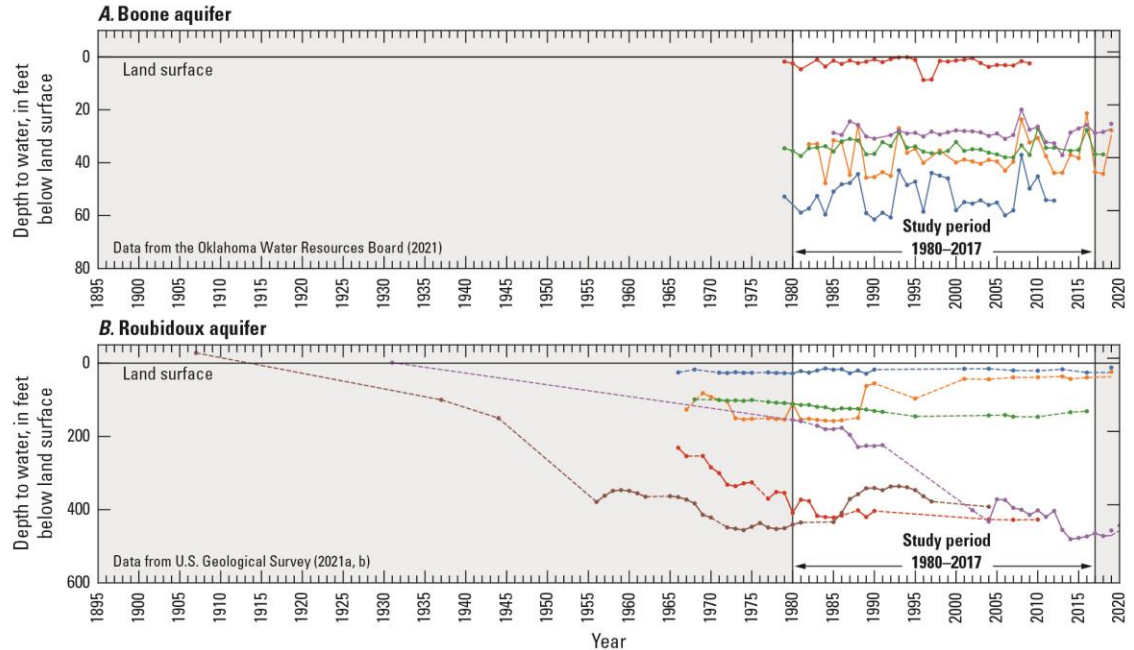
All non-domestic groundwater use is from the Oklahoma Water Resources Board's reported groundwater-use database (Chris Neel, Water Rights and Administration Division Chief, Oklahoma Water Resources Board, written commun., 2020). Domestic groundwater use is from Knierim and others (2017).



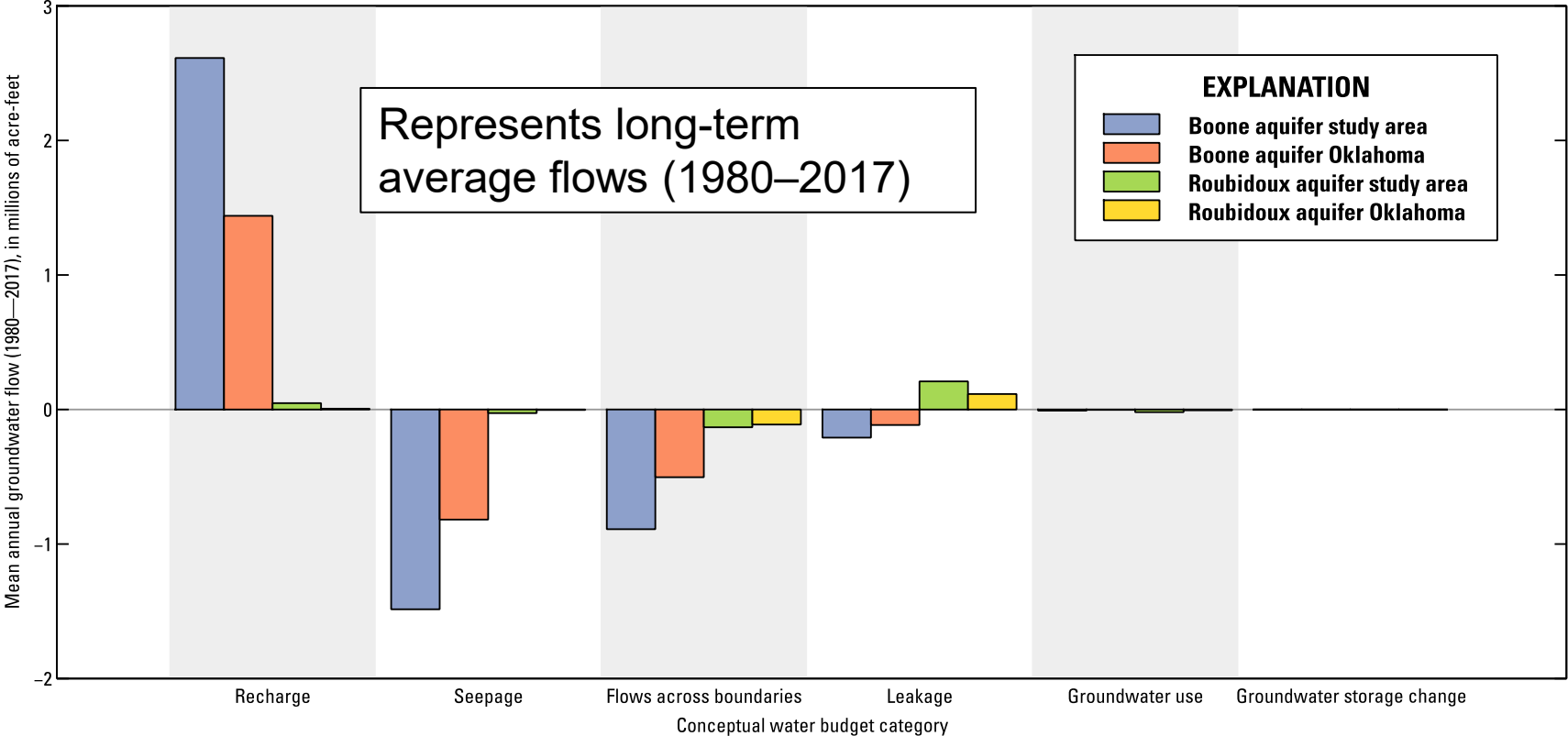
# Leakage, flows across boundaries, and changes in groundwater storage

- Leakage assumed 8 percent of recharge based on previous studies (Imes and Emmett, 1994)
- Changes in groundwater storage
  - 0 acre-ft
  - Relatively flat groundwater levels for most of the aquifer
- Flows across boundaries assumed to balance the inflows minus outflows after all other flows calculated

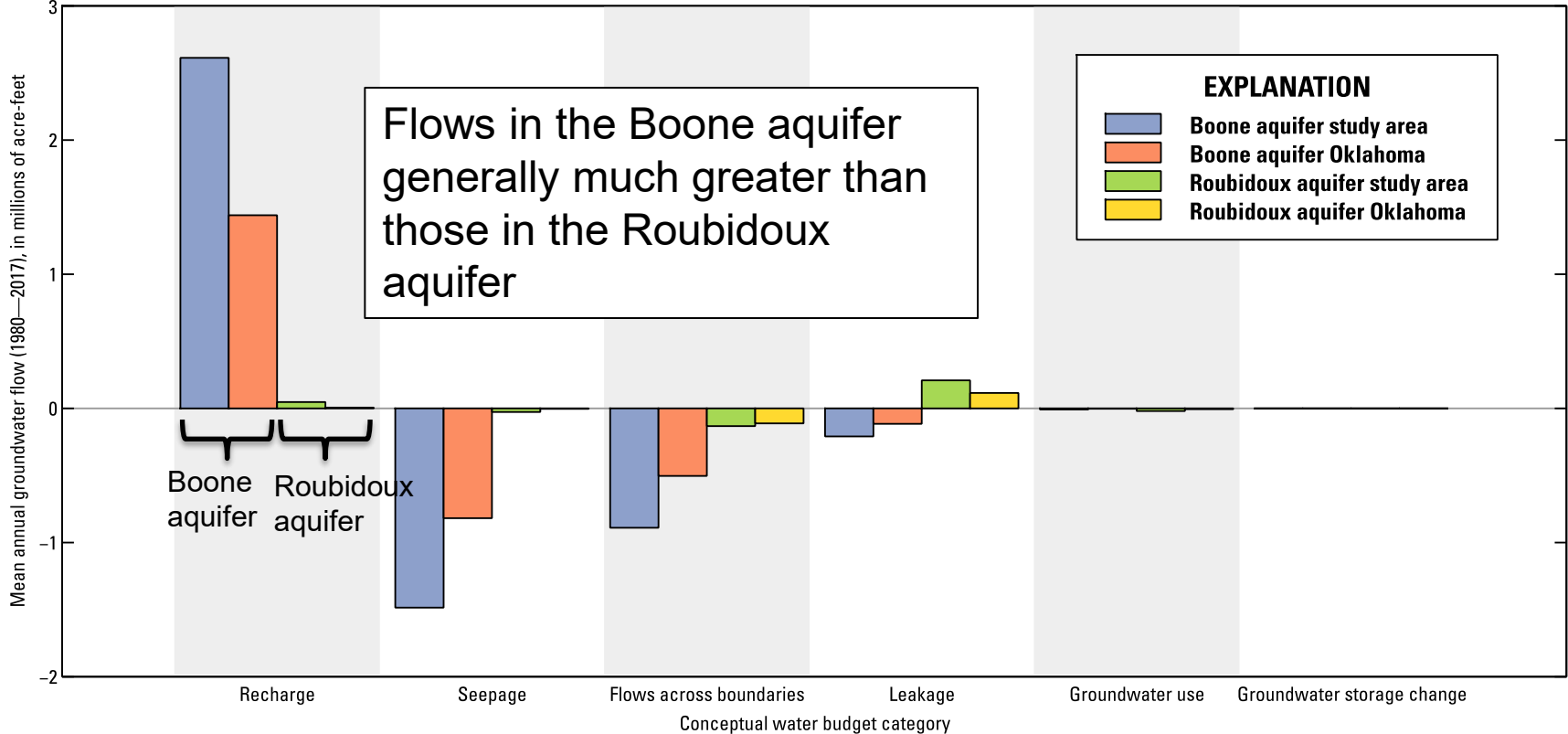
## Relatively flat groundwater levels



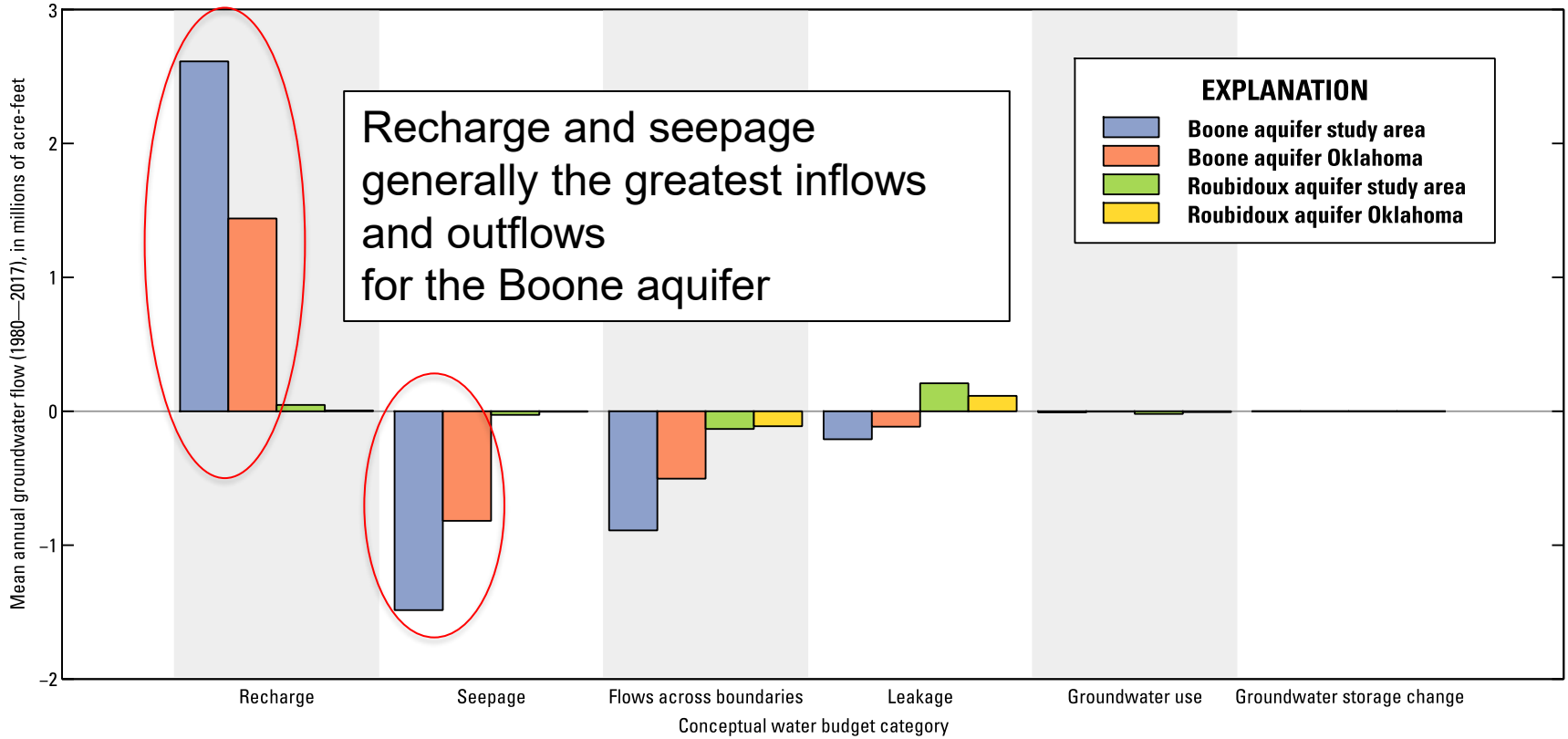
# Conceptual water budget



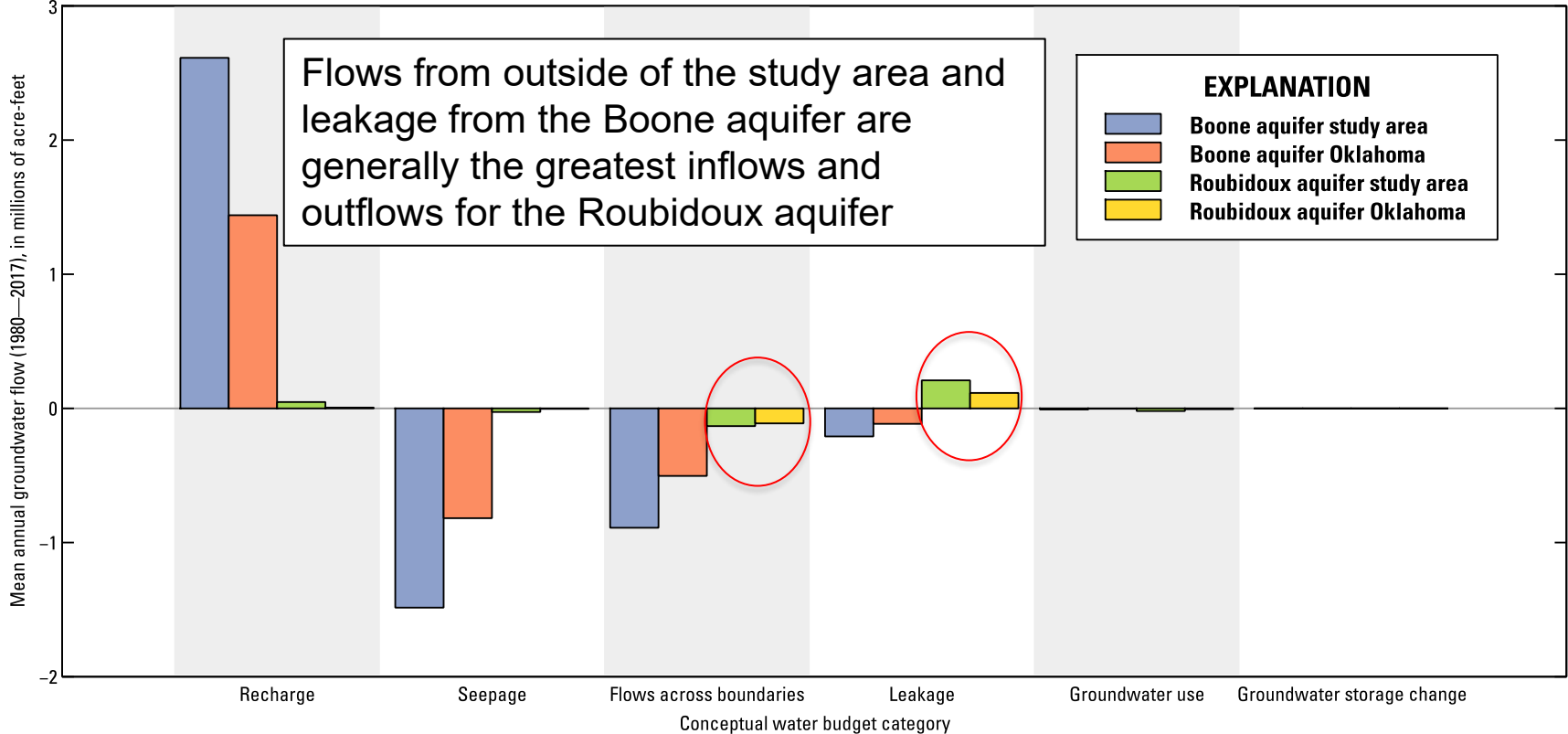
# Conceptual water budget



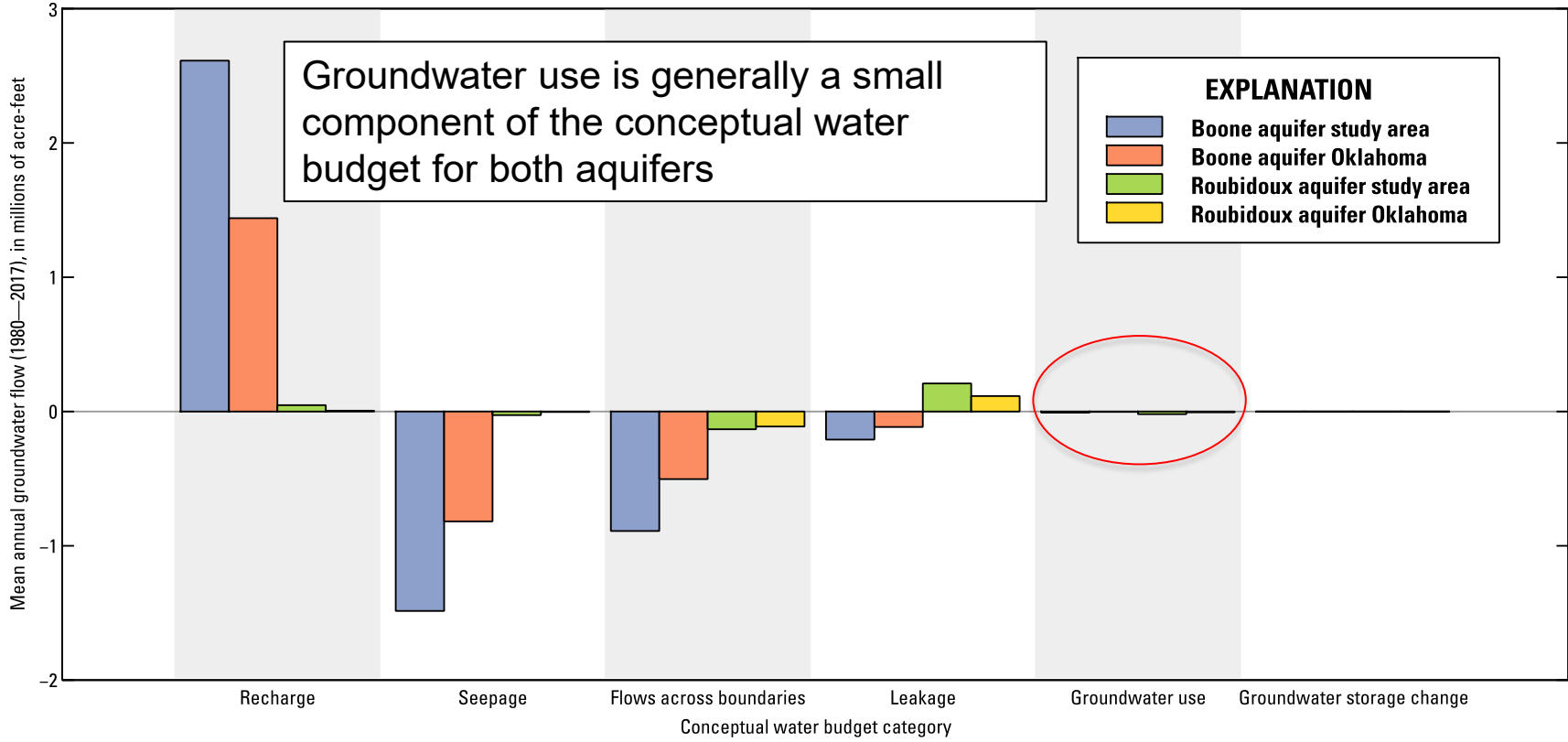
# Conceptual water budget



# Conceptual water budget

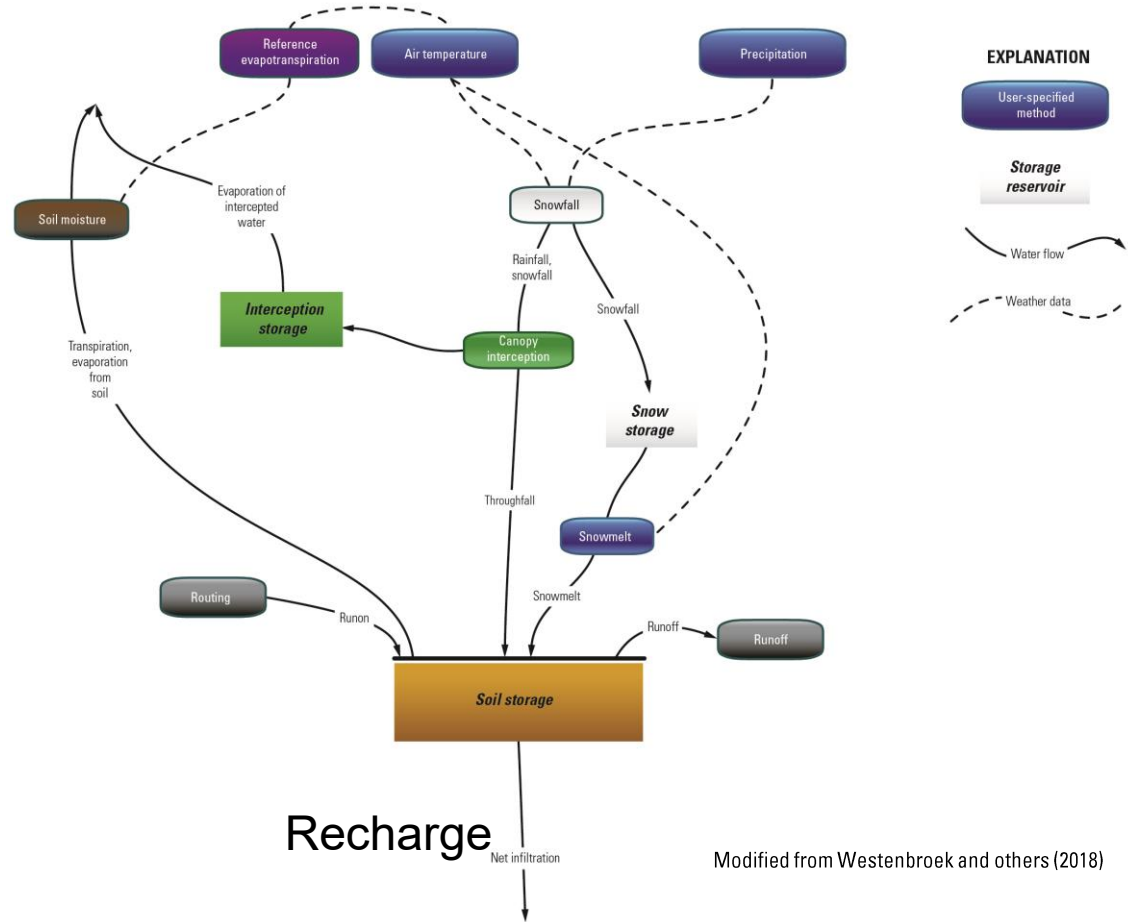


# Conceptual water budget



# Recharge – Soil-Water-Balance Model

- Model estimates recharge
- Can get better spatial representation of recharge than conceptual model methods
- Calibrated to conceptual model
- Outputs used as inputs to groundwater-flow model



# Groundwater-Flow Model

- MODFLOW-NWT finite differences groundwater flow model
- 4 layers – Western Interior Plains Confining System, Boone aquifer, Ozark confining unit, and the Roubidoux aquifer
- 2,000 ft cell size (approximately 92 acres)
- Simulates lakes, streams, springs, groundwater use, recharge and flows across boundaries

Flows across boundaries in pink

Wells in black







Streams in darker blue

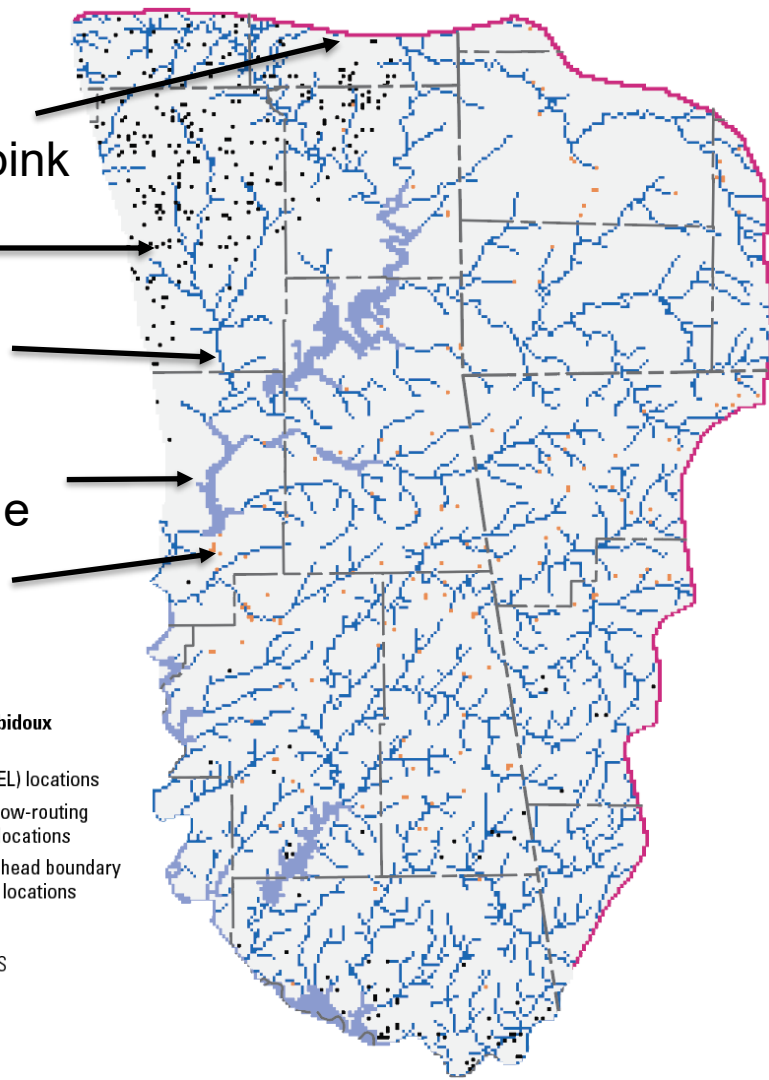
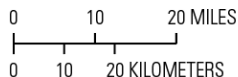
Lakes in lighter blue

Springs in orange

## EXPLANATION

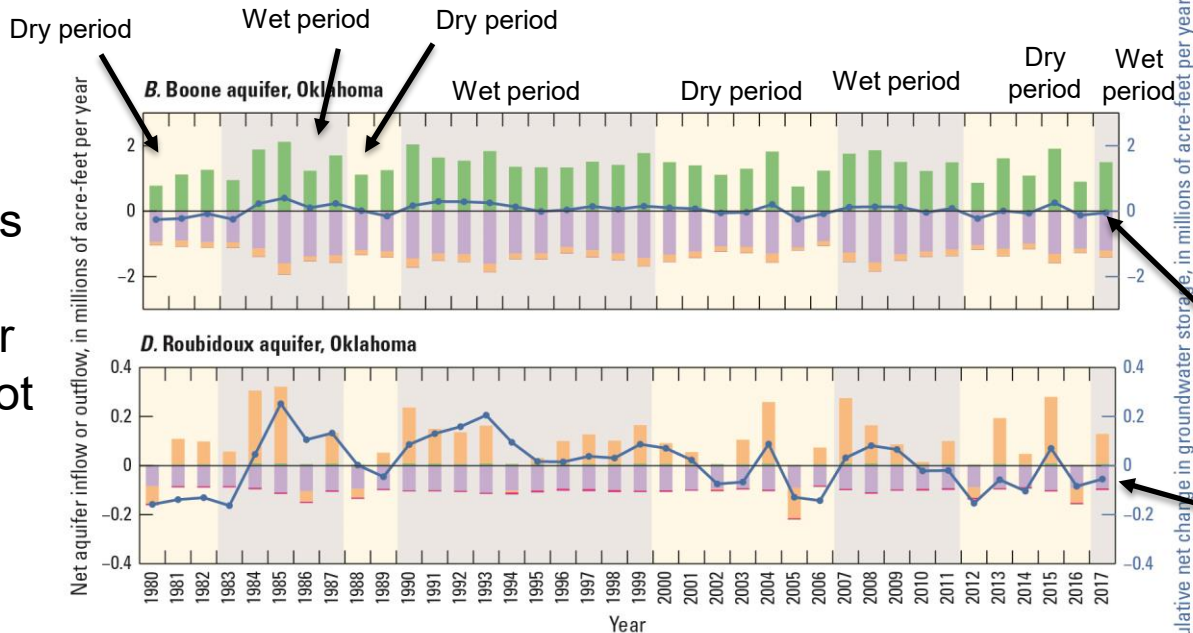
### Boundary conditions for the Boone and Roubidoux aquifer groundwater-flow model

 Active cell (no specified boundary condition)	 Well (WEL) locations
 Time-variant head (CHD) locations	 Streamflow-routing (SFR) locations
 Drain (DRN) locations	 General head boundary (GHB) locations



# Groundwater-Flow-Model Budget

Note: scale is almost 10 times greater for Boone plot



Cumulative net change in groundwater storage, in millions of acre-feet per year

Long-term change in groundwater storage close to zero

### EXPLANATION

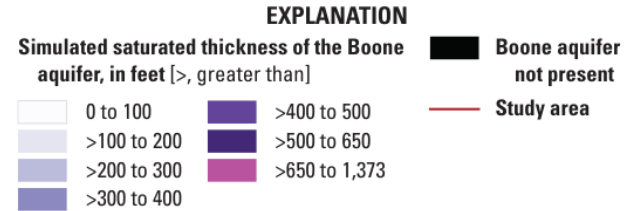
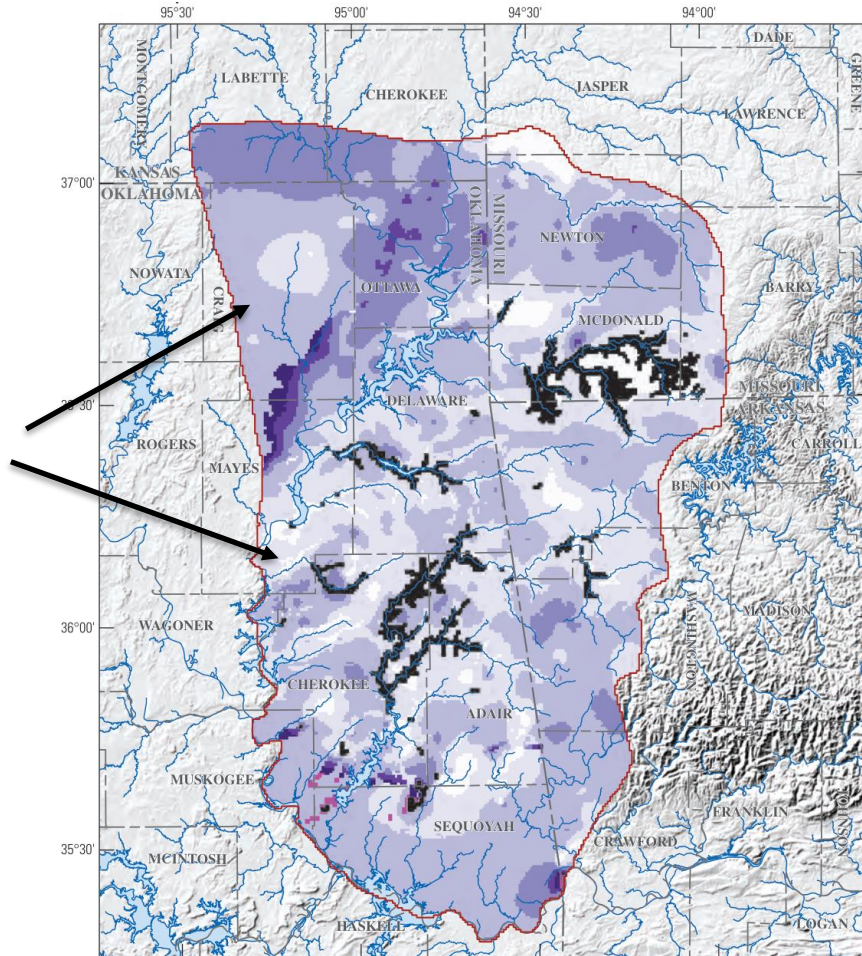
- Wet period (fig. 3)
- Dry period (fig. 3)
- Recharge
- Seepage
- Leakage
- Groundwater use
- Lateral flow across boundary
- Cumulative net change in groundwater storage

Note: Negative values indicate flows out of the aquifer or loss in groundwater storage, and positive values indicate flows into the aquifer or gain in groundwater storage.



# Groundwater-Flow Model– Boone Aquifer Saturated Thickness 2017

Mostly 100  
to 300 ft  
saturated  
thickness

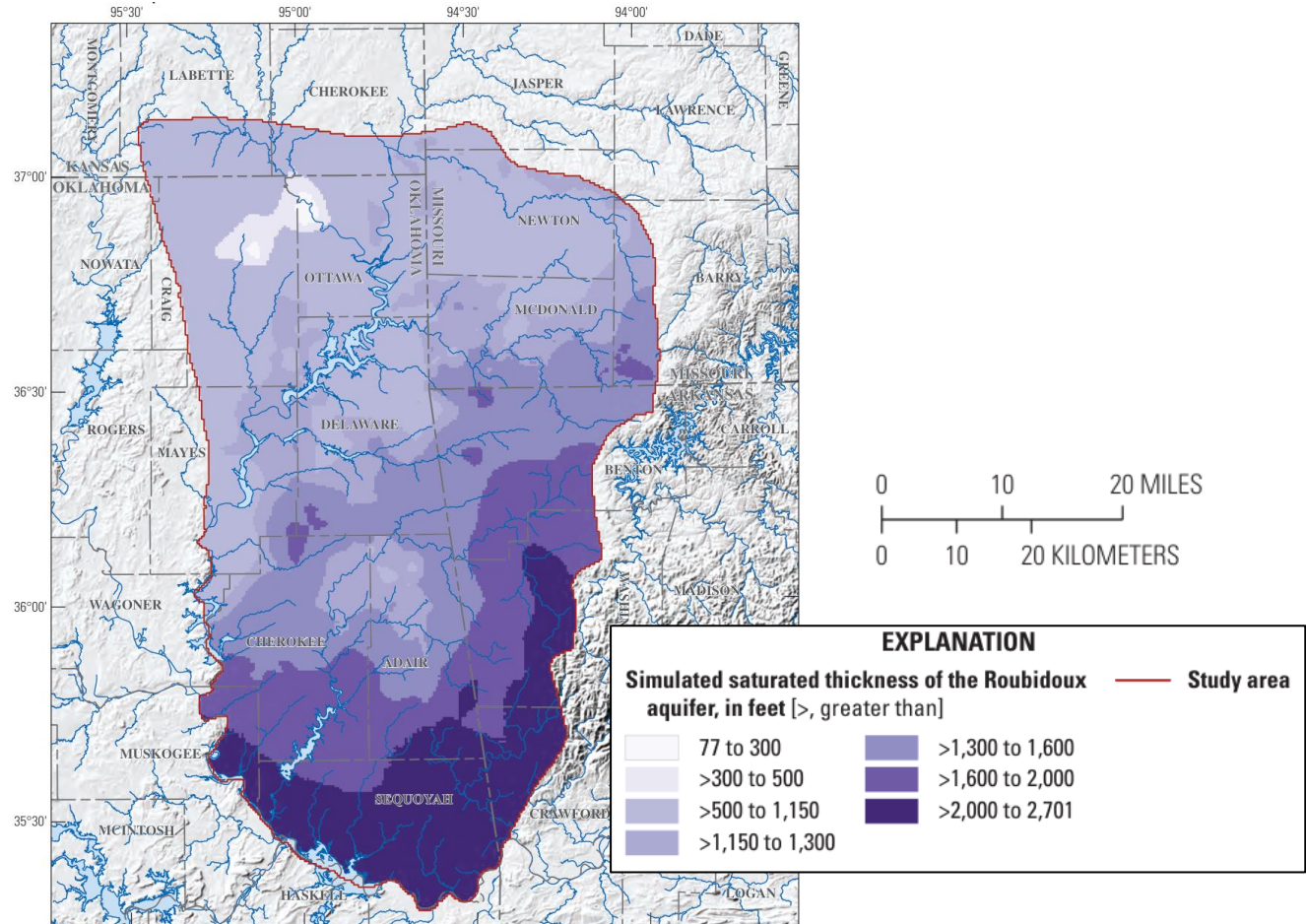


Note: Areas where the saturated thicknesses were greater than 650 feet coincide with areas where the rocks that contain the Western Interior Plains confining unit have eroded, or coincide with the thickest part of the Boone aquifer in the southeastern part of the study area.



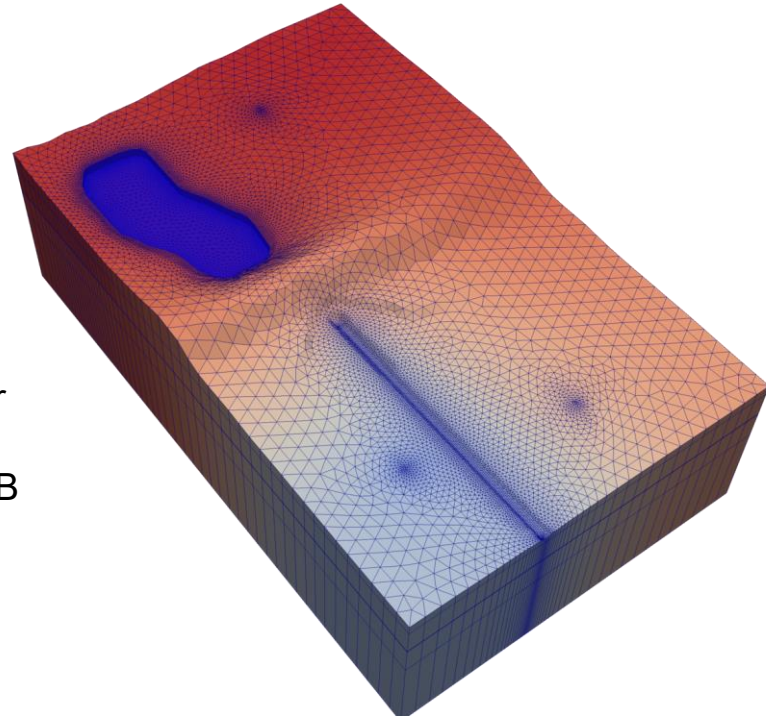
# Groundwater-Flow Model– Roubidoux Aquifer Saturated Thickness 2017

- More variable than Boone Aquifer
- Mostly more than 500 ft saturated thickness
- Much more saturated thickness in southern part of the aquifer



# Groundwater-Flow Model Scenarios

- Future projections
  - Equal-proportionate-share
    - Assess the aquifer response to groundwater withdrawals equally apportioned in each cell over the aquifer (fully developed)
    - Minimum 20-year life of aquifer
      - Median saturated thickness 15 feet after 20 years of EPS groundwater withdrawals
  - Projected 50-year groundwater withdrawals
    - Scale groundwater withdrawals by 58 percent over 50 years based on projections of increases in groundwater withdrawals determined by the OWRB (OWRB, 2012)
- Historical hypothetical 10-year drought
  - Select historical period (1990–99) not in drought
  - Simulate drought conditions
  - Compare groundwater flows in the aquifer between drought and no drought



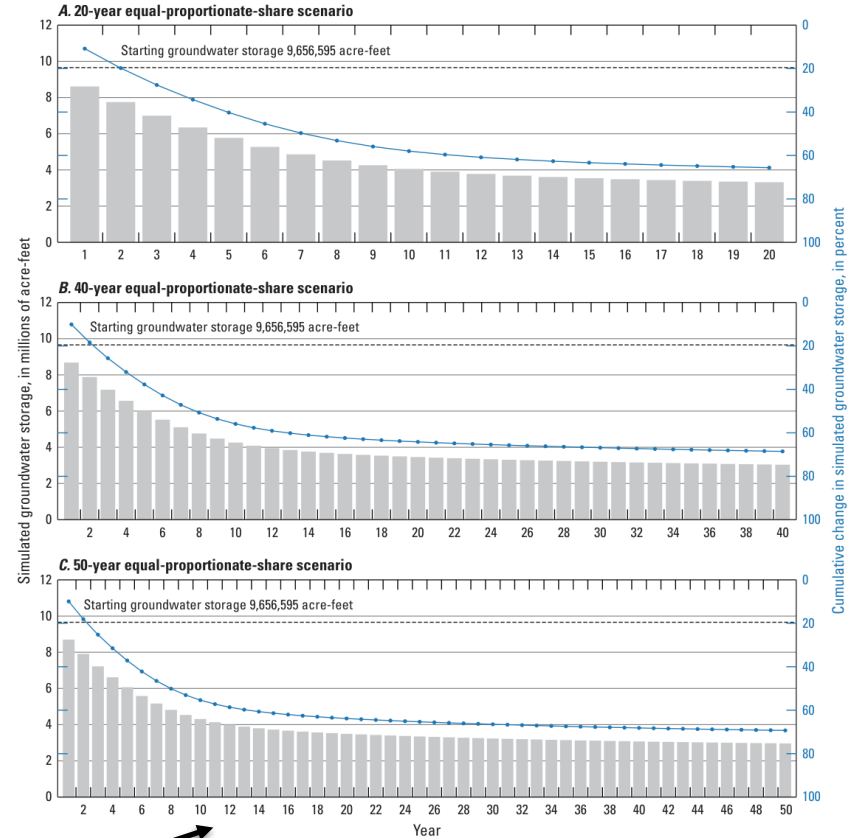
# Groundwater-Flow Model– Equal-Proportionate-Share Scenario Boone Aquifer

- All flows held constant except groundwater withdrawals
- About 70 percent reduction in groundwater storage at the end of each simulation
- EPS rates represent about 1,000 times more than 2018 groundwater withdrawals (0.0008 [acre-ft/acre]/yr)

## Boone aquifer

[in/yr, inches per year]

Fraction of normal recharge <sup>2</sup>	Normal recharge <sup>2</sup> after scaling, in in/yr	EPS Rate <sup>1</sup> , in acre-feet per acre per year		
		20 years	40 years	50 years
0.9	8.29	1.01	0.90	0.87
1	9.21	1.10	0.98	0.96
1.1	10.13	1.18	1.06	1.04



Years projected after 2017



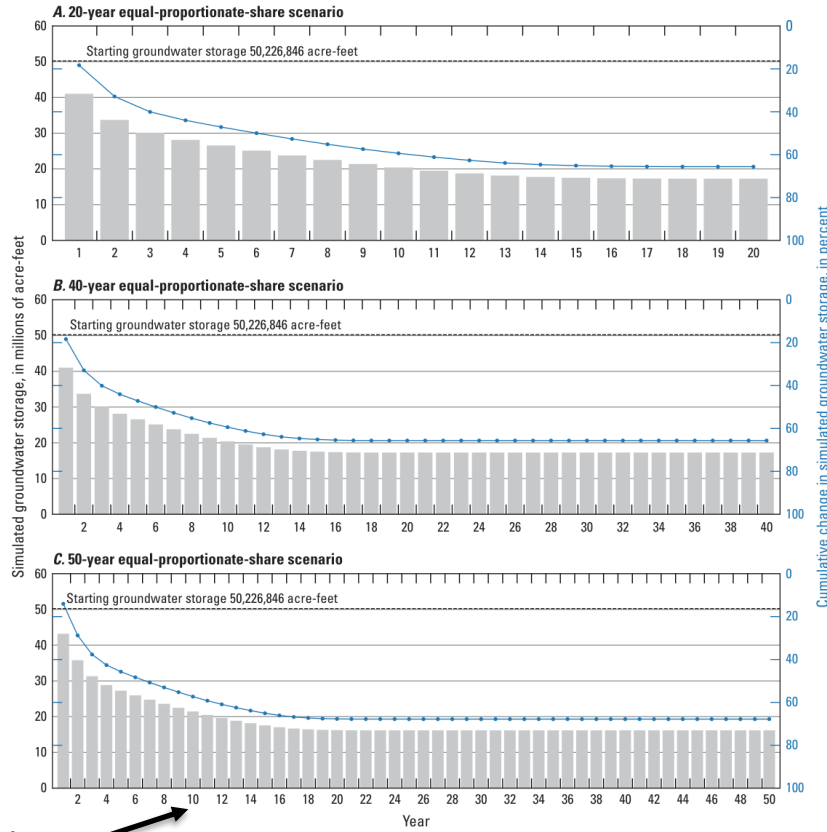
# Groundwater-Flow Model– Equal-Proportionate-Share Scenario Roubidoux Aquifer

- All flows held constant except groundwater withdrawals
- About 70 percent reduction in groundwater storage at the end of each simulation
- EPS rates represent about 100 to 1,000 times more groundwater withdrawals than 2018 groundwater withdrawals (0.002 [acre-ft/acre]/yr)
- Leakage adjusted for no leakage from Boone aquifer

[in/yr, inches per year; (acre-ft/acre)/yr, acre-feet per acre per year]

Simulated years	Fraction of normal recharge <sup>1</sup>	Normal recharge <sup>1</sup> after scaling, in in/yr	EPS groundwater withdrawal rate, <sup>2</sup> in (acre-ft/acre)/yr	Leakage-adjusted EPS groundwater withdrawal rate, <sup>3</sup> in (acre-ft/acre)/yr
20-year	0.9	8.29	1.68	0.60
	1.1	9.21	1.76	0.60
40-year	0.9	8.29	1.26	0.32
	1	9.21	1.34	0.32
	1.1	10.13	1.41	0.32
50-year	0.9	8.29	1.17	0.26
	1	9.21	1.25	0.26
	1.1	10.13	1.32	0.26

<sup>1</sup>Normal recharge was averaged over the study area for the 1980–2017 study period.  
<sup>2</sup>An EPS rate is the maximum allowed annual groundwater-withdrawal rate for an aquifer per acre of land owned or leased by the permit holder (Oklahoma Secretary of State, 2023).  
<sup>3</sup>The leakage-adjusted EPS rate varied when adjusting recharge but was small and cannot be discerned due to rounding.



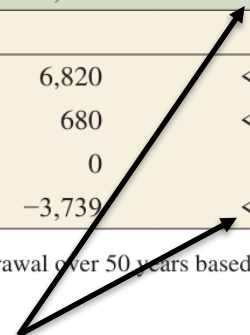
Years projected after 2017 →

# Groundwater-Flow Model– 50-year Projected Groundwater Use Scenario

[<, less than] 58 percent increase in groundwater withdrawals over 50 years

Projected 50-year groundwater-withdrawal simulation	Groundwater storage, in acre-feet		Change in groundwater storage	
	End of 2017-groundwater withdrawal-simulation	End of scenario	Acre-feet	Percent
Boone aquifer				
No groundwater withdrawal	9,806,665	9,812,658	5,993	0.06
Mean groundwater withdrawal rate, 1980–2017	9,806,665	9,807,904	1,239	0.01
2017 groundwater withdrawal rate	9,806,665	9,806,665	0	0.00
Increased demand groundwater withdrawal rate <sup>1</sup>	9,806,665	9,803,276	–3,389	–0.03
Roubidoux aquifer				
No groundwater withdrawal	50,302,531	50,309,351	6,820	<0.01
Mean groundwater withdrawal rate, 1980–2017	50,302,531	50,303,211	680	<0.01
2017 groundwater withdrawal rate	50,302,531	50,302,531	0	0.00
Increased demand groundwater withdrawal rate <sup>1</sup>	50,302,531	50,298,792	–3,739	<0.01

<sup>1</sup>The increasing demand groundwater withdrawal rate assumed a cumulative 58-percent increase in groundwater withdrawal over 50 years based on 2010–60 demand projections for southern Oklahoma (Oklahoma Water Resources Board, 2012b).



Small fraction of a percent change in groundwater storage

# Groundwater-Flow Model– Hypothetical Drought Scenario

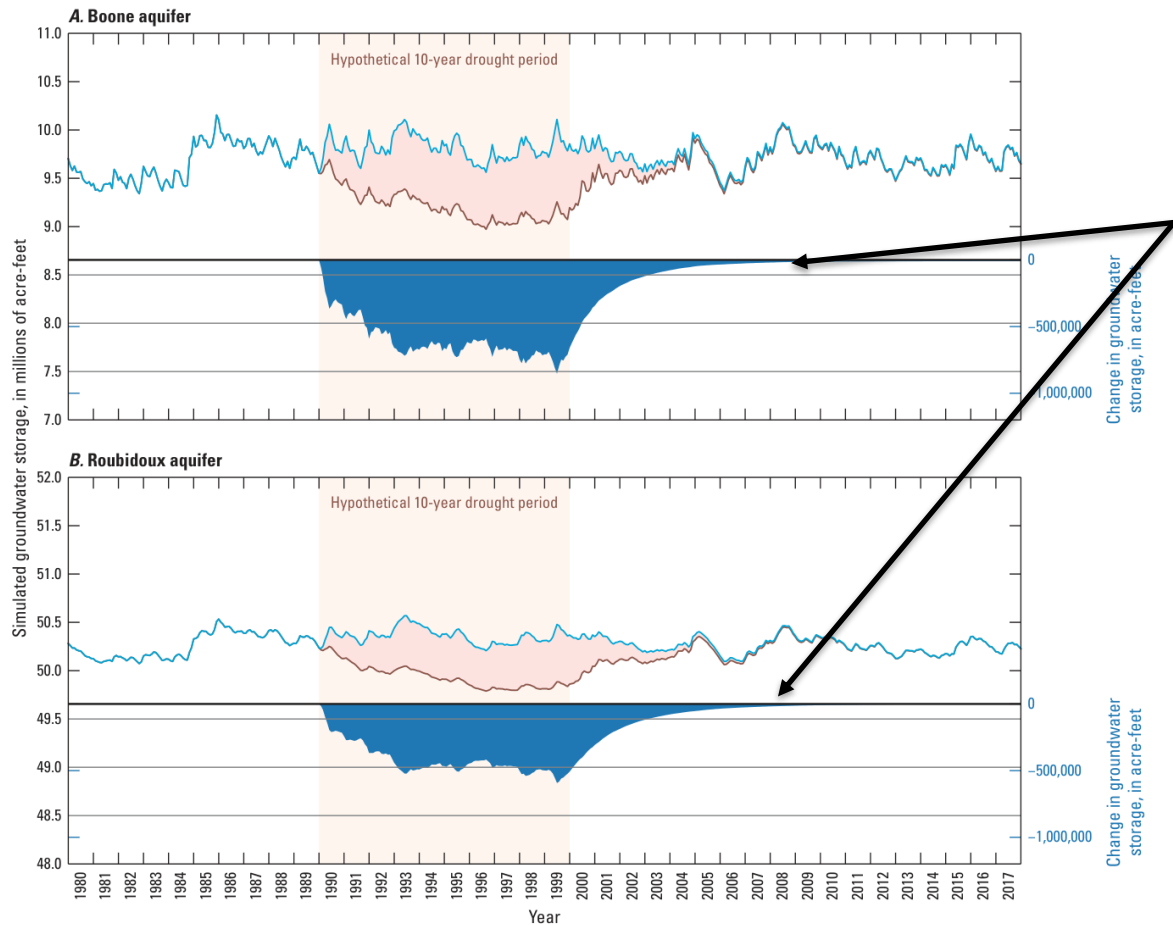
- Changed recharge from historical period (1990-99) to drought conditions
- Recharge reduced by 50 percent and stream inflows reduced by 75 percent to represent drought conditions

Hypothetical 10-year scenario (1990–99)				
Aquifer	Groundwater storage at the end of 1999 after 10 years of no drought or drought, in acre-feet		Change in groundwater storage after 10 years of drought, in acre-feet	Change in groundwater storage after 10 years of drought, in percent
	No drought <sup>1</sup>	Drought		
Boone aquifer	9,857,217	9,196,766	–660,451	–6.7
Roubidoux aquifer	50,368,653	49,860,181	–508,472	–1.0

<sup>1</sup>No drought refers to the simulation using the calibrated numerical model with historical climatic conditions.

Much higher percent change in groundwater storage than 50-year scenario.

# Groundwater-Flow Model– Hypothetical Drought Scenario

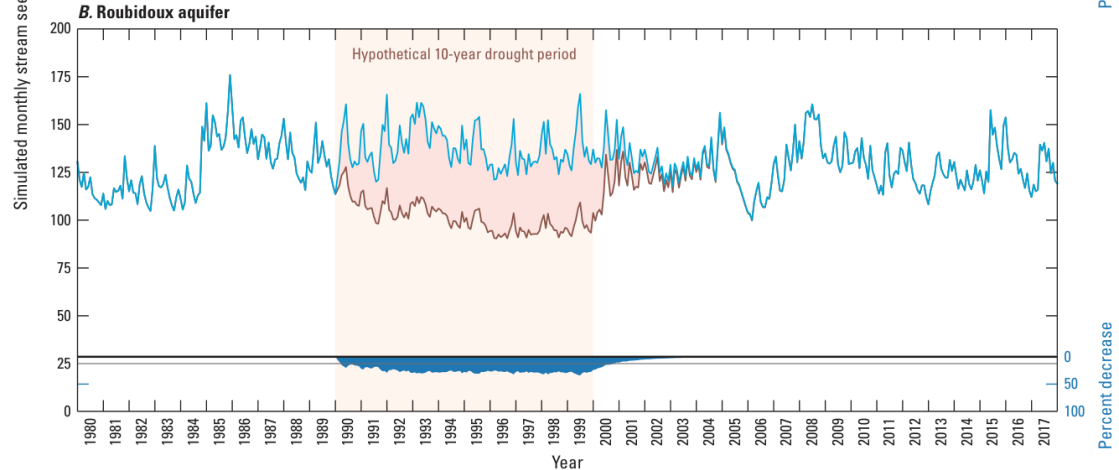
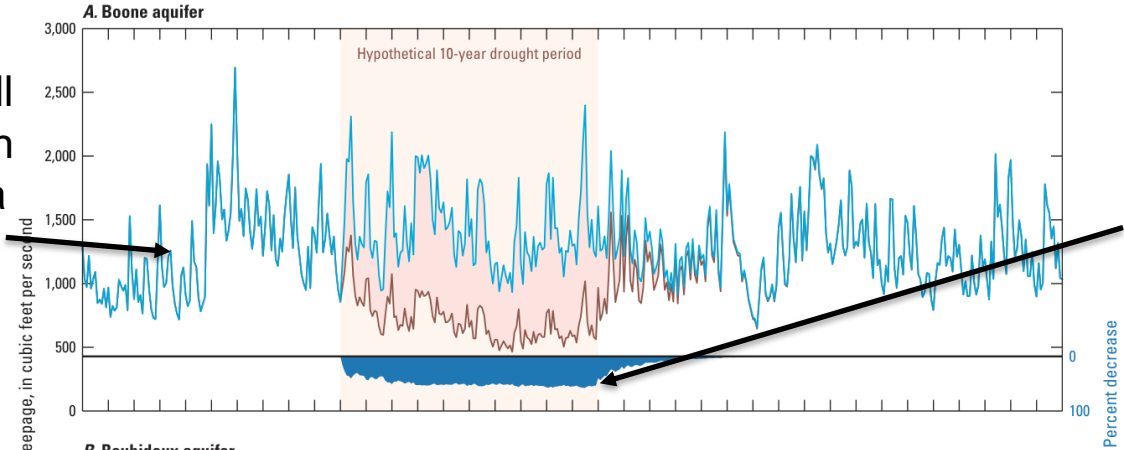


Recovery of groundwater storage took about a decade, although most recovery occurs in first 4 years after drought

# Groundwater-Flow Model– Hypothetical Drought Scenario

Represents all streamflows in the Oklahoma part of the aquifer

Streamflows decreased about 50 percent during the hypothetical drought

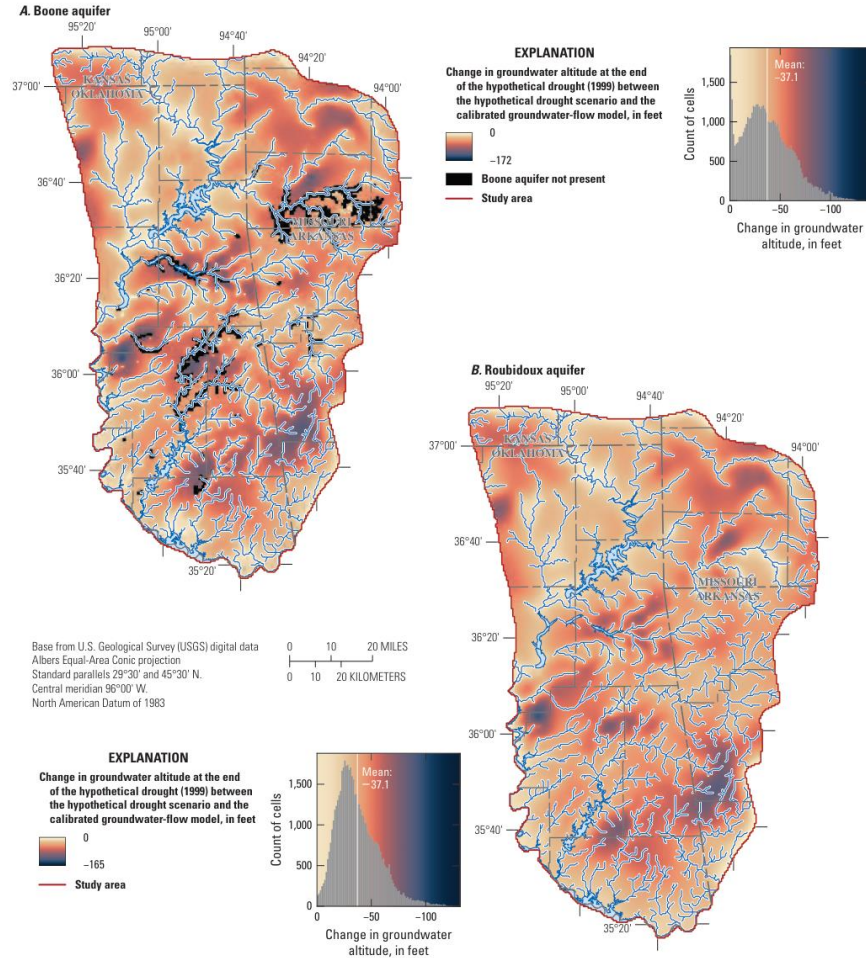


## EXPLANATION

- Change in simulated groundwater storage
- Difference in groundwater storage between drought and no drought
- Simulated groundwater storage, drought
- Simulated groundwater storage, no drought

# Groundwater-Flow Model– Hypothetical Drought Scenario

- Average change in groundwater altitudes about 37 ft.
- Largest decreases in groundwater altitude in central and southern parts of the aquifer.
- Boone and Roubidoux groundwater altitude changes were similar.
- “Lighter” color around the streams shows that streams are providing seepage to the aquifers.



# Summary

- Limitations
  - Represents region scale groundwater flows, may be different at a local scale or for a specific stream
  - Generalized model constructed as equivalent-porous-medium model
    - MODFLOW doesn't model karst well
    - No great options to model karst
    - Has been used for this aquifer previously
- Overall takeaways
  1. Groundwater availability in the Boone and Roubidoux aquifers is relatively stable
  2. Groundwater withdrawals represent a small component of the model budget
  3. Changes in climate likely have more of an impact than groundwater withdrawals unless groundwater withdrawals greatly increase
  4. The OWRB uses the results of this study to help determine the EPS and MAY. Often, the EPS and MAY are different than those determined by groundwater-flow modeling. For more information see:

<https://oklahoma.gov/content/dam/ok/en/owrb/documents/science-and-research/hydrologic-investigations/maximum-annual-yield-determinations-fact-sheet.pdf>

# Questions?

Contact Shana Mashburn with any follow up questions:

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