Climatic Controls on Streamflow and Groundwater Dynamics in a Semi-Arid Catchment: Long-Term Trends and Importance of Episodic Events (1940-2023)

UNIVERSITY OF COPENHAGEN

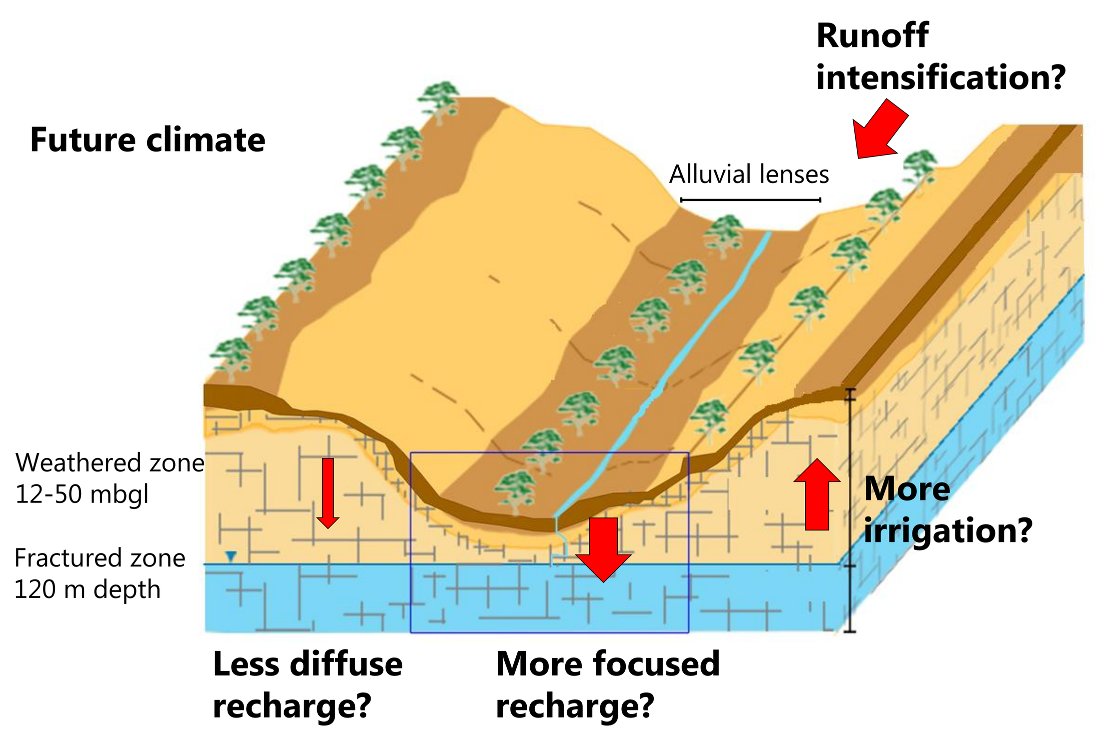
Elisa Bjerre[1], Trine Enemark[1], Søren Jessen[1], and Karsten Høgh Jensen[1]
[1]Institute for Geosciences and Natural Resource Management, University of Copenhagen, Denmark
Contact: elbj@ign.ku.dk

Sharing is encouraged

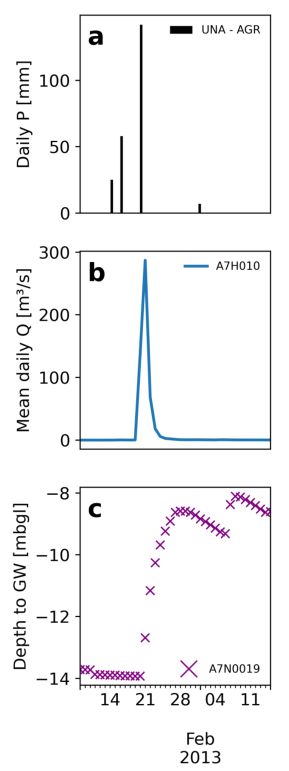
1) Introduction

Groundwater is a vital water source in **semi-arid South Africa**, dominated by **erratic precipitation** and **ephemeral river flow**. Water scarcity is critical due to population growth, increasing irrigation demands, and climate change. Groundwater recharge predominantly occurs as episodic events and specifically as **focused recharge** during high river flow. Thus, understanding and quantifying the relationships between climate, streamflow and groundwater dynamics is crucial to assess the **impact of climate change** on future water availability, and to develop sustainable groundwater management practices. Our research questions are:

- How does **climate change** influence streamflow dynamics and groundwater levels?
- Is **focused recharge** the dominant recharge process and is it changing over time?
- What is the importance of **episodic events** on streamflow and groundwater recharge?



Schematic illustration of catchment processes. Modified from [4].

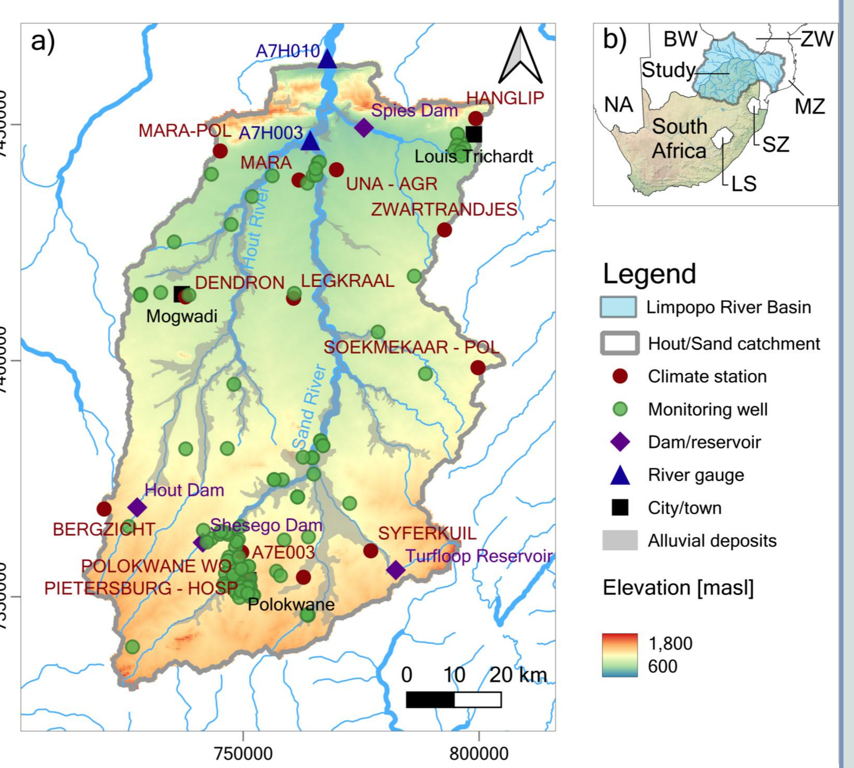


a) Episodic precipitation (P) event, b) streamflow (Q) response, and c) groundwater (GW) increase (focused recharge).

2) The Hout/Sand Catchment

- Limpopo River tributary.
- Area: 7,722 km².
- Dominant geology: Gneiss.
- Groundwater-fed irrigation.
- Evidence of groundwater depletion.
- Lack of data for constraining traditional hydrological models.

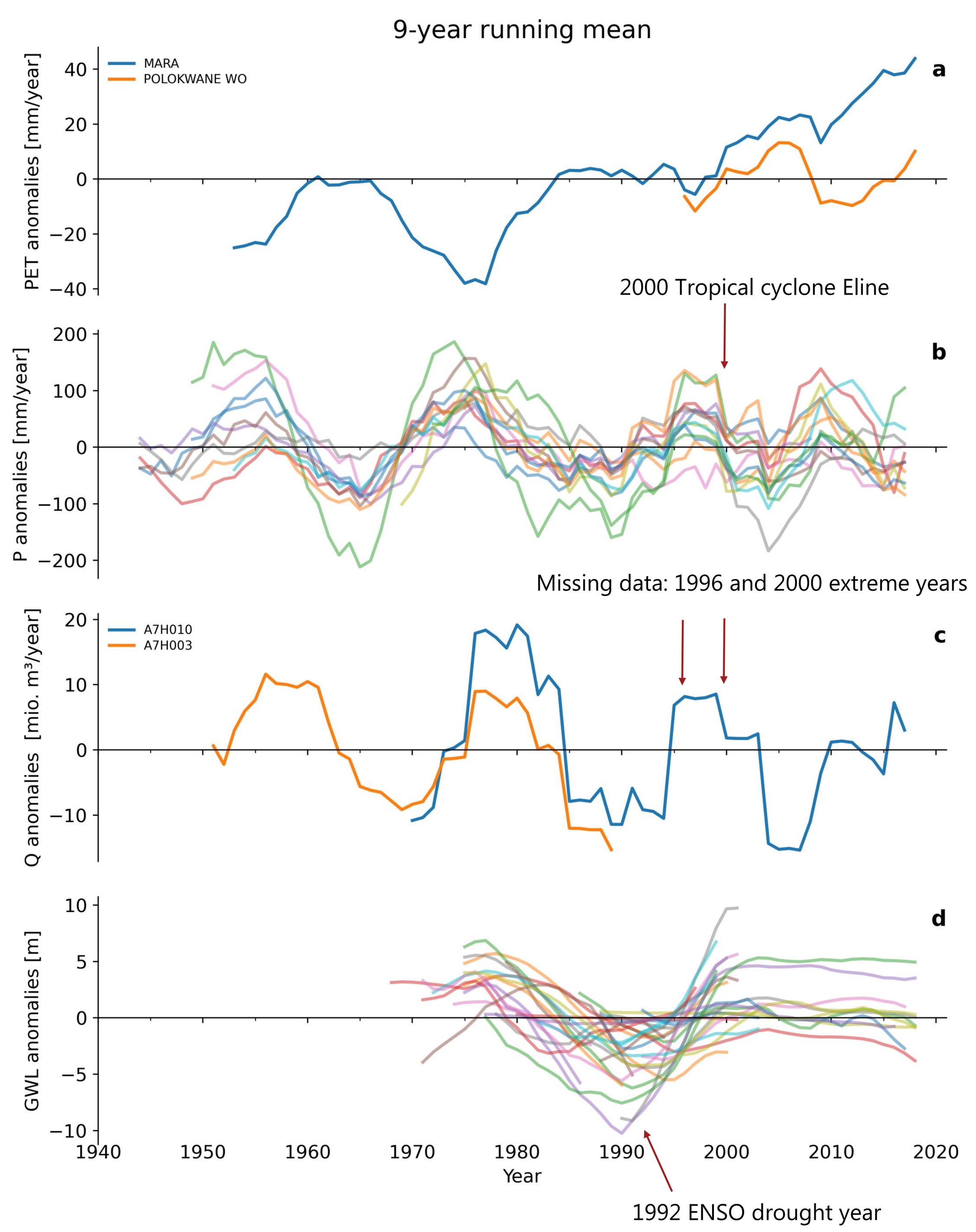
The Sand River. Source: https://www.esgusa-dfc.com,



3) Results

A. Long-term trends in hydro-climate

Dominant climatic variability follows a 17-20 year cycle associated with the major modes of global and regional climate variability [3]. This decadal variability is observed in streamflow and groundwater levels.

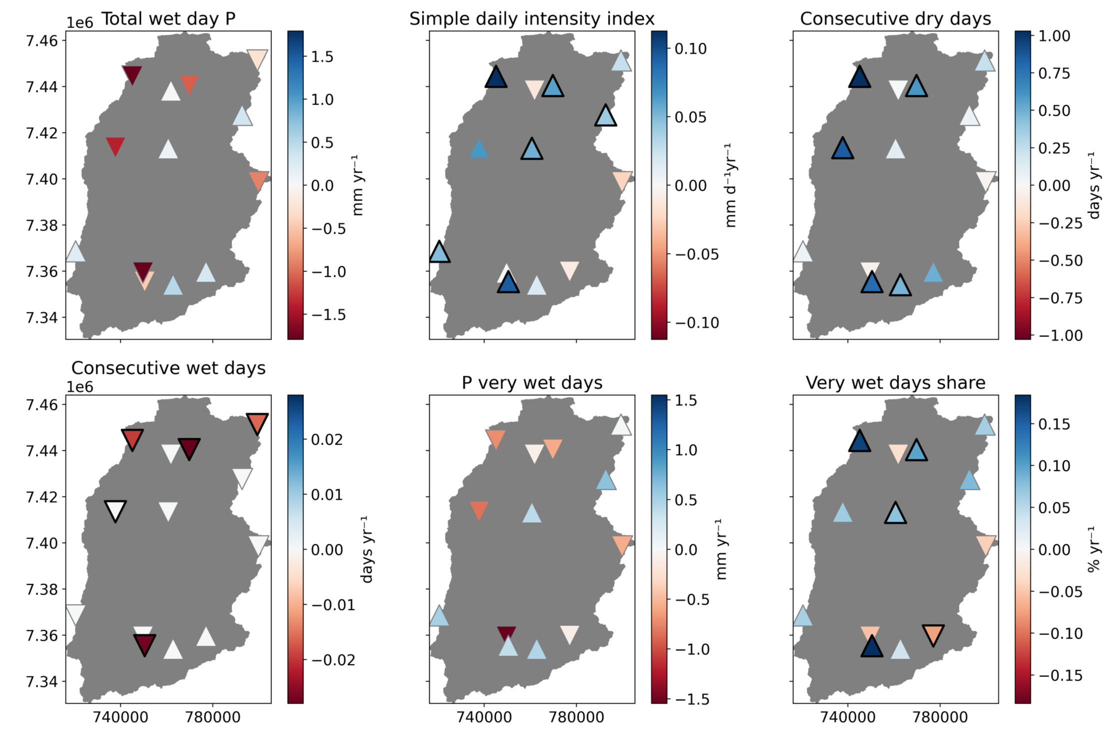


Anomalies in long term trends (9-year running mean) of a) potential evapotranspiration (PET), b) precipitation (P), c) streamflow (Q), d) groundwater levels (GWL) (>18 years). Each time series is centered by subtracting its mean.

B. Climate change 1940-2023

Daily max temperature increased 0.4 °C decade^{-1}. No significant trends in total annual precipitation. Significant trends indicating:

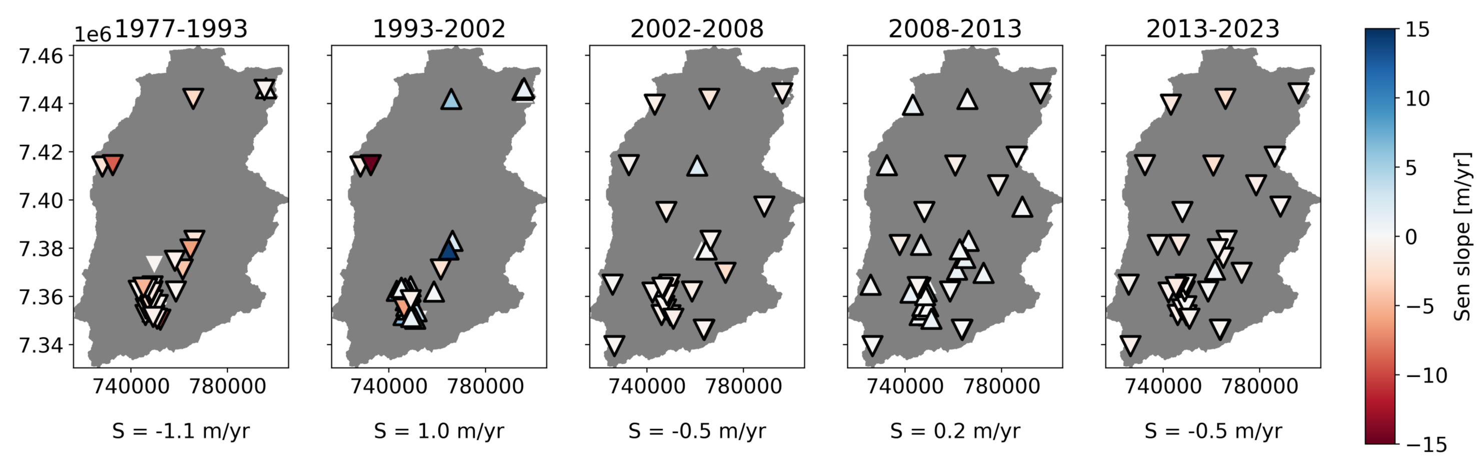
- Longer dry periods and shorter wet periods.
- More intense daily precipitation.
- Increasing contribution from extreme precipitation days.



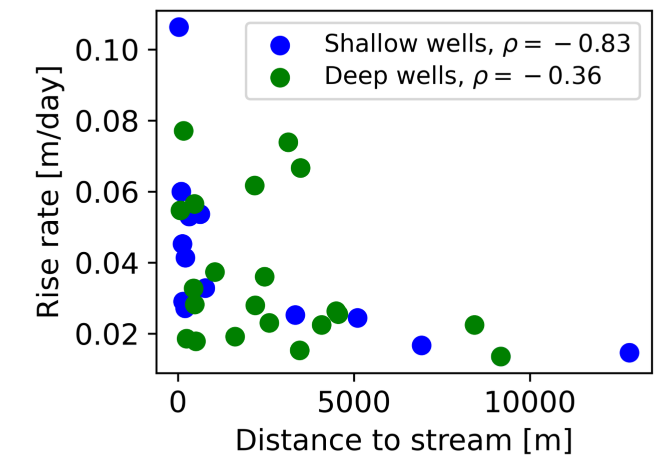
Trends in six annual precipitation indices. Triangles (weather stations) show the direction and magnitude of the Sen's slope (upwards + blue = positive, downwards + red = negative). Bold black lines = significant trends (p<0.05).

C. Streamflow and groundwater

Significant increase in duration of no-flow periods.
Groundwater increases during positive precipitation phases are becoming weaker.
High groundwater rise rates close to streams indicate focused recharge.



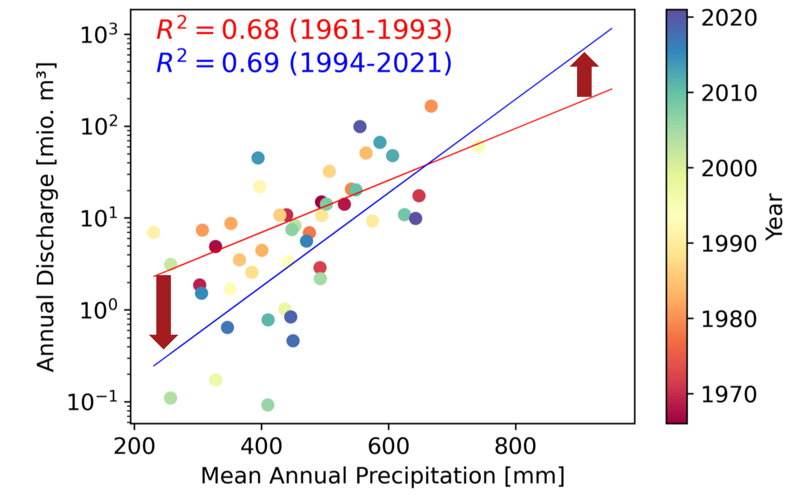
Groundwater level trends. Triangles (groundwater wells) show the direction and magnitude of the Sen's slope (upwards + blue = positive, downwards + red = negative). Bold black lines indicate significant trends (p<0.05). Below: median Sen's slope.



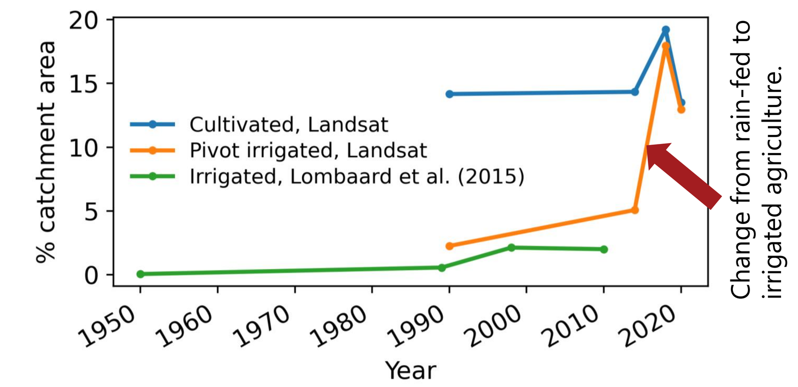
Spearman correlation coefficients between the groundwater signature 'rise rate' [1] and distance to stream for shallow (blue) and deep (green) groundwater wells.

D. Hydro-climatic relationships

Shift in streamflow response to precipitation over time.



E. Land use and irrigation



Evolution in land use as percentage of catchment area. Cultivated and pivot irrigated area derived from Landsat data, and total irrigated area from local authorities [4].

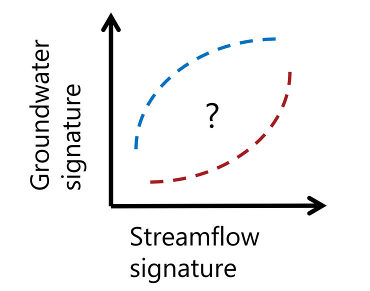
4) Conclusions

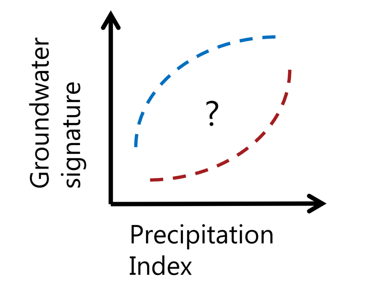
- Our results confirm regional changes in key climatic variables: increase in PET and **more episodic and extreme precipitation events**.
- Discharge data suggest **increasing dry periods in river flow**, but further conclusions are hampered by lack of data.
- The decadal climate patterns strongly influence the hydro-climate, emphasizing the **importance of long-term groundwater records** for evaluating trends.
- The years of high and low **groundwater levels** are correlated with **decadal precipitation anomalies**.
- Groundwater levels do **not fully recover from dry periods**, likely due to increased irrigation.
- Shift in relationship between annual precipitation and annual discharge suggests **more extreme discharge response to precipitation**.

5) Future Work

- Analyze relationships between groundwater level dynamics and streamflow, climatic and physiographic characteristics.
- Use machine learning regression techniques to identify the most important controls on focused recharge in order to perform spatial regionalization.

Predictors: Hydro-climatic Physiographic → Machine learning model → Groundwater level dynamics





MINISTRY OF FOREIGN AFFAIRS OF DENMARK
Danida

Acknowledgements:
This project was funded by Danida, Ministry of Foreign Affairs of Denmark.
We acknowledge our partners at University of Western Cape, University of Pretoria, Water Cycle Innovation, Ekosource and the Geological Survey of Denmark and Greenland.
Hydro-climatic data was provided by the Department of Water and Sanitation, South Africa and the South African Weather Service.

References:
[1]Collenteur, R.A., Bakker, M., Caljé, R., Klop, S.A., Schaars, F. (2019) Pastas: open source software for the analysis of groundwater time series. Groundwater.
[2]Lombaard, J., Sikosana, S., & van Niekerk, E. (2015). *The Development of the Limpopo Water Management Area North Reconciliation Strategy, Hydrological Analysis, Volume 1: Main Report, Department of Water and Sanitation, South Africa*.
[3]Malherbe, J., Dieppois, B., Maluleke, P., Van Staden, M., & Pillay, D. L. (2016). South African droughts and decadal variability. *Natural Hazards*, *80*(1), 657–681.
[4]Manna, F., Murray, S., Abbey, D., Martin, P., Cherry, J., & Parker, B. (2019). Spatial and temporal variability of groundwater recharge in a sandstone aquifer in a semiarid region. *Hydrology and Earth System Sciences*, *23*(4), 2187–2205.