Groundwater Recharge Variability in a Semi-Arid Catchment under Climate Change: Insights from Long-term Observations and Machine Learning

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1) Introduction

- In **semi-arid** regions groundwater is often the only perennial freshwater source for sustaining ecosystems and human use.
- **Focused recharge** - groundwater replenishment via seepage from rivers during high flow – is known to contribute substantially to groundwater storage at local scale.
- Yet, the relative contributions of focused and **diffuse recharge**, as well as their dependence on **climate change**, remain poorly understood at **catchment scale**.

Research questions:

- What is the long-term **spatio-temporal variability** in groundwater recharge?
- Is **focused** or **diffuse recharge** the dominant recharge process at catchment-scale and is it changing over time?
- Does focused recharge act a as a **climate change buffer**?

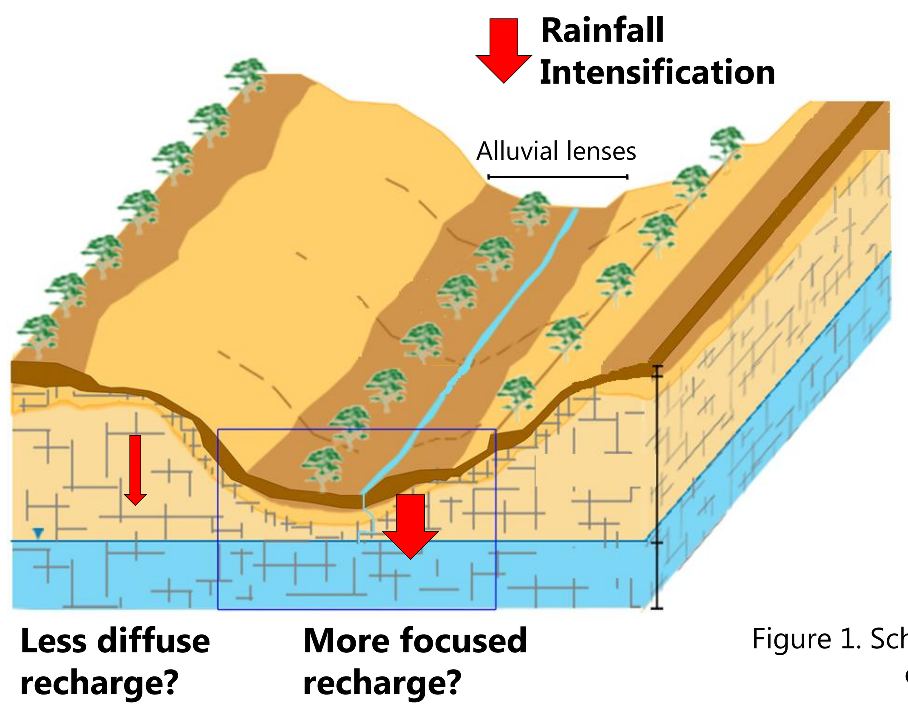

Figure 1. Schematic illustration of catchment processes. Modified from [1].

2) Study site

- Hout/Sand River Catchment, Limpopo, South Africa.
- Weathered and fractured gneiss aquifer overlain by alluvial deposits along major tributaries.
- Climatic intensification during 1940-2022, with increasing temperatures, longer dry periods and rainfall intensification [2]

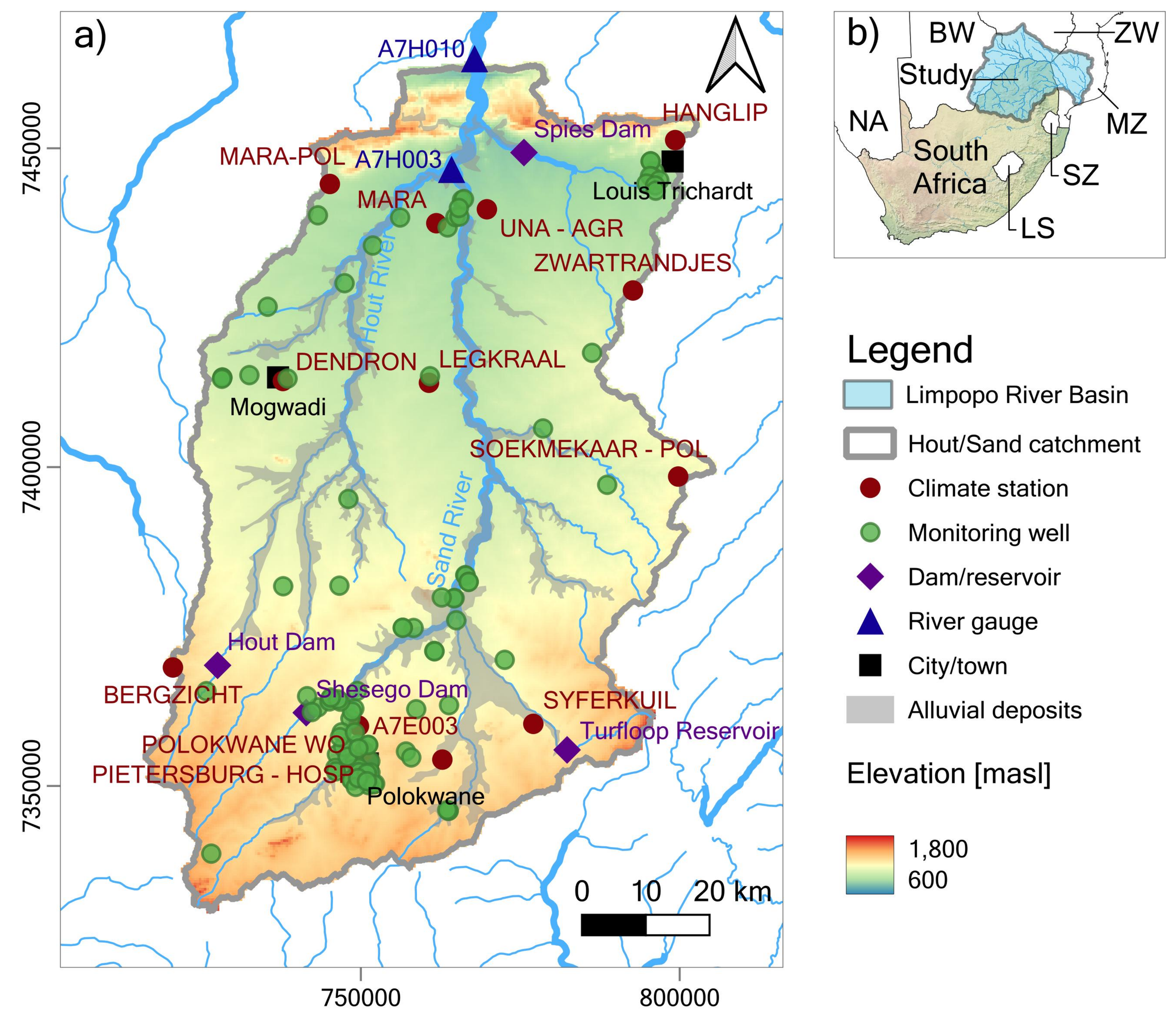

Figure 2. a) Hout/Sand catchment (7,722 km²). b) Location within the Limpopo River Basin.

3) Data and Methods

Water Table Fluctuation Method

- 97 individual groundwater hydrographs scattered over the period 1970–2021 (Fig 3).
- 1,508 annual recharge estimates were derived using the Water Table Fluctuation (WTF) method [3].

Machine Learning Recharge model

- A Light Gradient-Boosting Machine (LightGBM) model was developed to generate annual recharge maps at a 100 m resolution for the period 1970-2021.
- The model was trained on the WTF-derived recharge estimates employing 17 physiographic and climatic predictors.

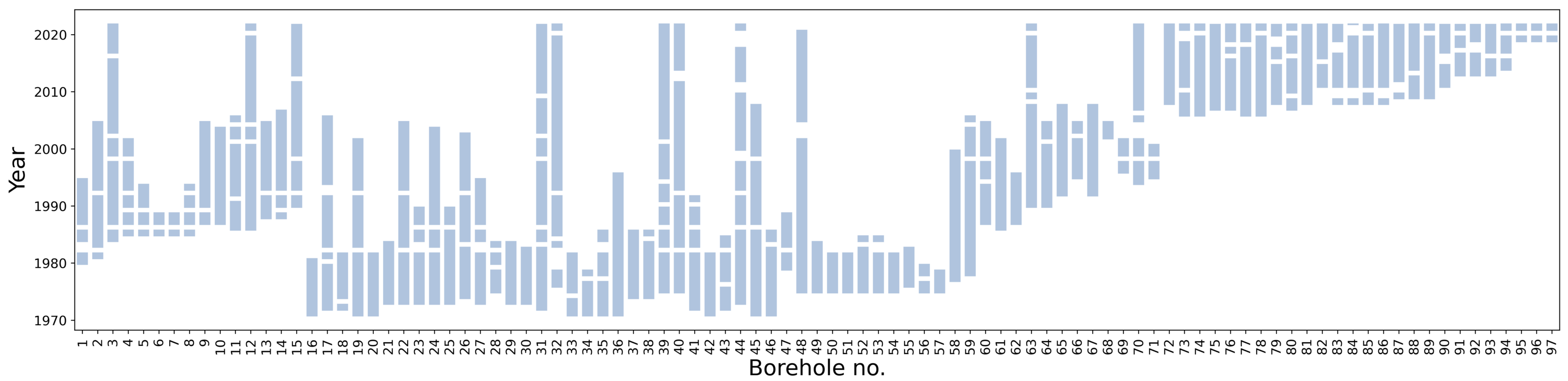

Figure 3. Hydrograph data availability for the 97 boreholes.

4) Results

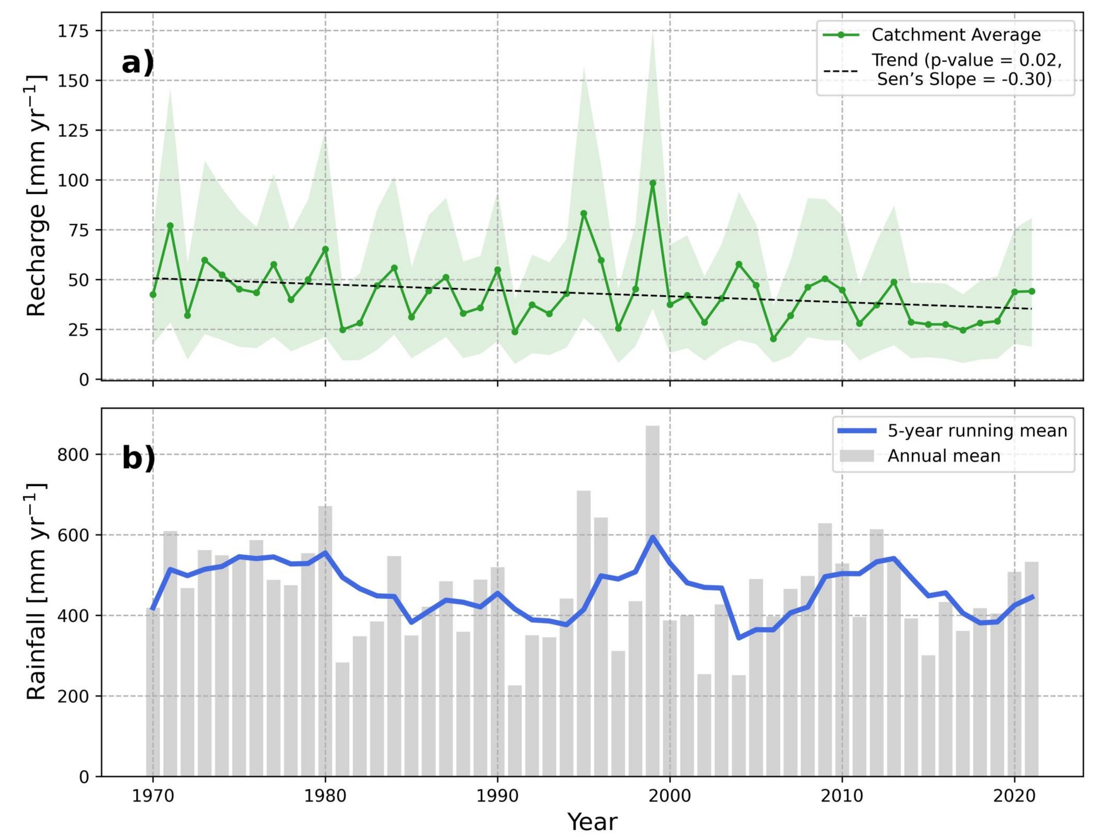

Figure 4. Mean annual recharge, shaded areas show parameter uncertainty related to specific yield. b) Mean annual rainfall.

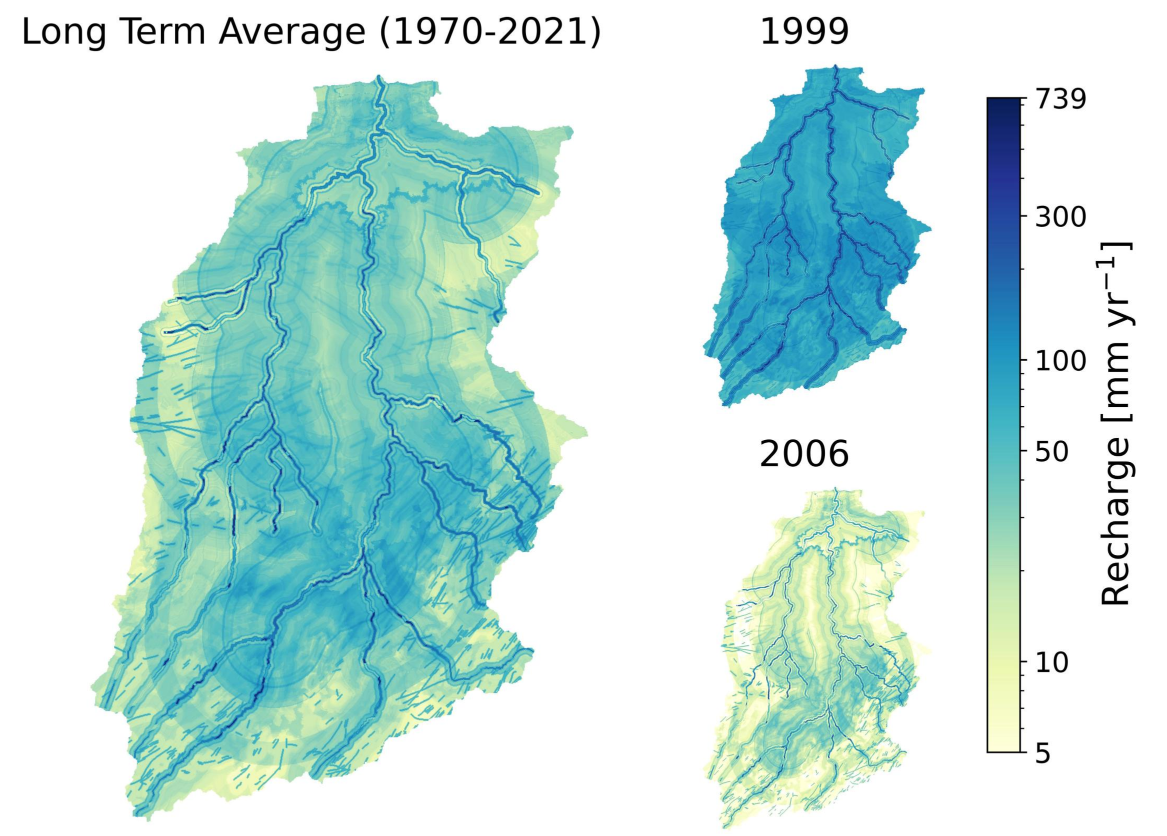

Figure 5. a) Long-term average annual recharge 1970-2021. Annual recharge for 1999 (b) and 2006 (c).

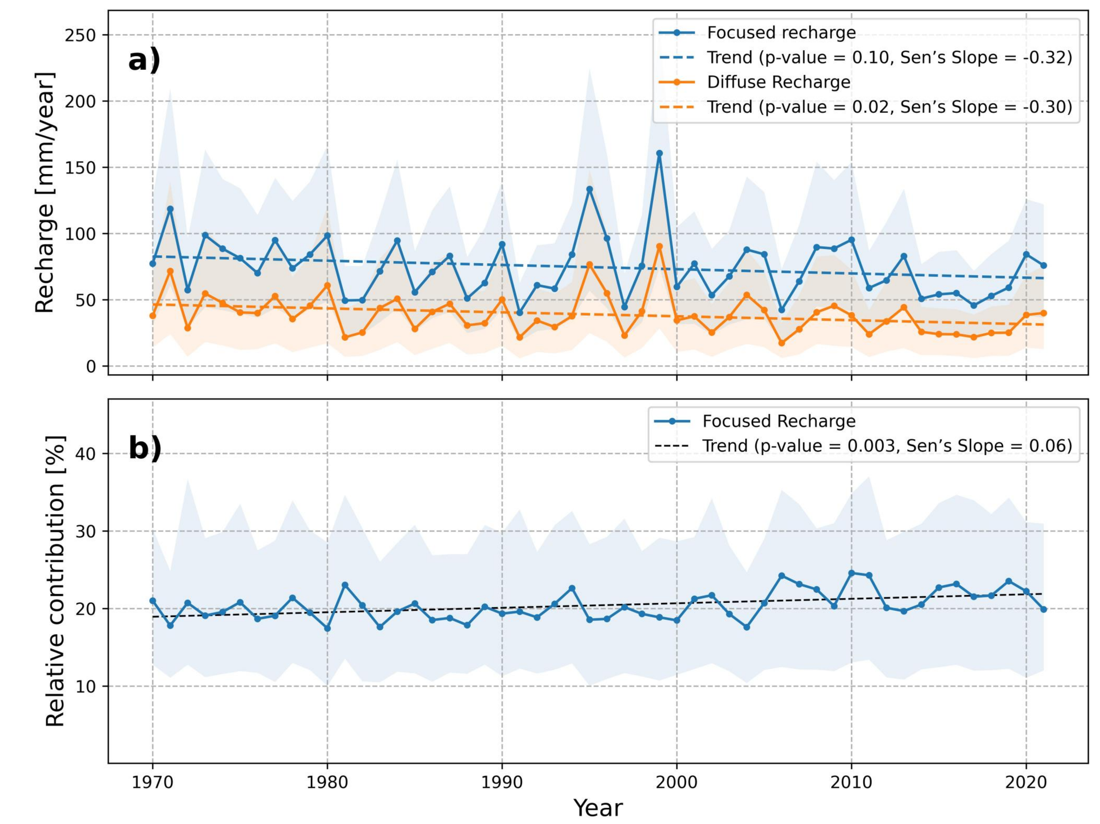

Figure 6. a) Diffuse and focused annual recharge. b) Relative contribution of focused recharge to catchment-scale recharge. Shaded areas show parameter uncertainty related to specific yield.

Model evaluation

- LightGBM: **me:** 5.2 **mae:** 134.0 **rmse:** 300.5 **r:** 0.92.

Spatio-Temporal Recharge Variability

- Catchment-scale recharge is decreasing 3mm/decade 1970-2021.
- Spatial recharge patterns confirm prevalence of focused recharge along riverbeds.

Focused and Diffuse Recharge

- Focused and diffuse recharge are both decreasing, although diffuse recharge at a higher rate.
- The relative contribution of focused recharge to catchment-scale recharge is increasing, with an average contribution of 20%.

5) Conclusions and Outlook

- Our results suggest that focused recharge is gradually becoming a more dominant component of total groundwater replenishment.
- On average, focused recharge contributes 20% of catchment-scale recharge, though this contribution is highly sensitive to the specific yield values used in the WTF method.
- There is a great potential in using machine learning models to overcome the issue of scattered and gap-filled data.
- Future work will investigate how the relative contribution of focused recharge correlates with rainfall patterns and climate intensification.

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