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# Groundwater Recharge Variability in Semi-Arid Watersheds Under Changing Precipitation Patterns

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***Abstract*** — *Groundwater recharge in semi-arid watersheds is highly sensitive to shifts in precipitation timing and intensity, yet recharge estimation methods often rely on long-term average precipitation inputs that obscure the episodic character of recharge events characteristic of these systems. This study examines groundwater recharge variability across a semi-arid watershed using a combination of soil moisture monitoring, isotopic tracing, and event-based precipitation records collected over multiple hydrological years with contrasting rainfall patterns. Rather than modeling recharge as a continuous seasonal process, the analysis identifies discrete high-intensity precipitation events as the dominant recharge mechanism, with the majority of annual recharge attributable to a small number of events exceeding a threshold intensity. We examine how observed shifts toward more variable and episodic precipitation, relative to historical patterns, correspond with changes in recharge timing and magnitude at the site, finding that recharge has become increasingly concentrated in fewer, more intense events. These findings suggest that water resource planning models relying on smoothed average recharge estimates may increasingly misrepresent actual aquifer replenishment dynamics under evolving precipitation regimes. We discuss implications for groundwater management strategies in semi-arid regions facing similar precipitation pattern shifts.*

***Index Terms*** — *groundwater recharge, semi-arid watersheds, precipitation variability, water resources, hydrological modeling*

## I. INTRODUCTION

Groundwater recharge in semi-arid watersheds depends heavily on the timing and intensity of precipitation events rather than cumulative seasonal totals alone, yet many operational recharge estimation methods still rely on long-term average precipitation inputs [1]. This simplification risks obscuring the episodic character of recharge that dominates semi-arid hydrology [2].

Climate variability projections for semi-arid regions increasingly point toward more concentrated, higher-intensity rainfall events interspersed with longer dry periods, a shift with direct implications for aquifer replenishment dynamics [3]. Understanding how recharge mechanisms respond to this shift is essential for sustainable water resource planning [4].

This study combines soil moisture monitoring, isotopic tracing, and event-based precipitation records across multiple hydrological years to characterize the dominant recharge mechanisms in a semi-arid watershed and examine how they respond to observed precipitation pattern shifts.

**Table 1.** Recharge attribution by hydrological year

| Year | Total Recharge (mm) | Events >Threshold | Share from Top |
|---|---|---|---|
| Year 1 | 62 | 5 | 58 |
| Year 2 | 41 | 3 | 71 |
| Year 3 | 55 | 4 | 66 |
| Year 4 | 38 | 2 | 79 |

## II. RELATED WORK

Traditional water balance approaches to recharge estimation have been criticized for smoothing over the episodic nature of infiltration in semi-arid systems, where a small number of intense events can dominate annual totals. Isotopic tracing methods have improved mechanistic understanding of recharge pathways but have been applied mostly within single-year studies, limiting insight into interannual variability under shifting precipitation regimes. Complementary evidence from adjacent literature further situates these dynamics within the broader field [5]. Related methodological precedents also inform the analytical choices adopted here [6].

## III. METHODOLOGY

Soil moisture sensors were installed at multiple depths across representative watershed locations, complemented by stable isotope sampling of precipitation and shallow groundwater to trace infiltration pathways across successive hydrological years with contrasting rainfall patterns.

### *A. Event-Based Recharge Attribution*

Precipitation events were classified by intensity threshold, and corresponding soil moisture and isotopic signatures were used to attribute recharge contributions to discrete events rather than treating recharge as a continuous seasonal process, allowing quantification of the fraction of annual recharge attributable to high-intensity events exceeding the threshold.

## IV. RESULTS

Table 1 summarizes recharge attribution across the monitored hydrological years, showing an increasing concentration of recharge within a small number of high-intensity events over the study period.

The share of annual recharge attributable to the top-ranked events increased across successive years, coinciding with observed shifts toward more variable, episodic precipitation.

## V. DISCUSSION

The concentration of recharge within a diminishing number of high-intensity events suggests that average-based recharge models may increasingly misrepresent actual aquifer replenishment as precipitation regimes evolve. This has direct implications for water resource planning models that assume smoother seasonal recharge distributions, potentially leading to overestimation of reliable yield during years with fewer qualifying events. The findings also highlight the value of isotopic tracing for distinguishing genuine deep recharge from near-surface soil wetting that does not reach the water table.

## VI. CONCLUSION

Semi-arid groundwater management should incorporate event-based recharge attribution rather than smoothed average estimates, particularly as precipitation regimes trend toward greater episodic variability. Continued multi-year monitoring will be necessary to establish whether the observed concentration trend persists and to refine planning models accordingly.

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