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Temporally clustered streamflow events control focused groundwater recharge in drylands

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Abstract

Groundwater (GW) is the primary freshwater resource in many of the world's drylands, sustaining millions of people and supporting agriculture and ecosystems where surface water is scarce or unreliable. Recharge in these regions is highly episodic and occurs mainly through ephemeral streams (i.e. focused recharge), yet the mechanisms that determine whether surface flows contribute to aquifer replenishment remain poorly constrained. A common assumption is that large floods dominate recharge, but evidence from long-term monitoring is limited and inconclusive. We combine a unique hydrogeological monitoring dataset from the arid zone (Fowlers Gap in western New South Wales, Australia) with numerical modelling of vadose zone processes to assess the controls on focused GW recharge. Our results show that even extreme floods that overtopped piezometers did not produce measurable recharge at the water table. In contrast, significant recharge occurred only during a temporal cluster of moderate flow events in 2022. Numerical simulations confirm that temporal flow clustering produces longer periods of ephemeral streamflow, which progressively wet the vadose zone, overcome evapotranspiration (ET)-driven moisture deficits, and increase relative hydraulic conductivity, enabling percolation to the water table. Isolated floods, by contrast, largely saturate only shallow sediments and water is subsequently lost to ET. By explicitly incorporating ET, our modelling provides a more realistic representation of dryland recharge dynamics and highlights the roles of antecedent conditions and vadose zone properties. These findings demonstrate that recharge is not governed by rainfall totals or intensity alone, but critically depends on the timing and sequence of storm events. The implications for climate change assessments and water management are substantial, as projected shifts toward more intense but less frequent rainfall may reduce opportunities for clustering and thereby limit GW replenishment. Process-based modelling and event-scale analyses are therefore essential for reliable recharge projections and sustainable GW management in drylands.

1. Introduction

Groundwater (GW) is a vital resource in expanding drylands (i.e. arid and semi-arid regions), supplying millions of people and sustaining agriculture and ecosystems where surface water (SW) is scarce or unreliable [1]. It buffers against climatic extremes [2], enhancing resilience to droughts and variable rainfall [3]. Ephemeral streams are key recharge pathways [4], making GW the dominant freshwater source in many drylands [5]. However, widespread drying driven by declining precipitation and reduced streamflow has intensified drought, compounded by recent warming [6]. Effective water resource management therefore requires a detailed understanding of recharge processes and their sensitivity to climatic change [7].

Estimating recharge in drylands, where annual rainfall is lower than potential evapotranspiration (ET), is particularly challenging. Unlike humid regions, where diffuse infiltration dominates and can be approximated by one-dimensional models (e.g. [8, 9]), drylands experience limited rainfall (<400 mm yr^{-1}), high ET [10], and intermittent run-off [11]. In drylands, rainfall often generates run-off that concentrates in ephemeral channels, where some infiltrates to the aquifer (i.e. focused recharge) but most continues downstream (e.g. [12, 13]). Projected shifts toward fewer but more intense storms [14] are expected to amplify these dynamics [15].

In the drylands of southern Africa, recharge occurs primarily during extended or intense rainfall that enables deep infiltration through sandy and alluvial sediments. Focused recharge along ephemeral rivers can exceed diffuse recharge severalfold, as shown in the Limpopo Basin [16]. In central Tanzania, sandy floodplains and superficial deposits act as temporary reservoirs, providing recharge after major rainfall events [17]. Isotopic evidence from the Lake Chad Basin shows that recharge is dominated by heavy rainfall exceeding monthly intensity thresholds, highlighting its episodic nature [18].

Early work in semi-arid southern Africa recognised that GW recharge is rare and episodic, and is most likely to occur following prolonged wet periods or years with unusually large cumulative rainfall totals. For example, recharge occurrence was related to sustained above-average rainfall using GW-level responses and regional water-balance considerations [19], while similar observations were formalised into empirical recharge estimates and management-oriented rules of thumb [20]. Although these approaches provided valuable first-order guidance for water resource assessment, they express recharge thresholds in terms of cumulative rainfall magnitude and do not resolve the physical mechanisms by which hydraulic connectivity develops through thick vadose zones under strong ET and intermittent surface flow.

Ephemeral streams, activated by episodic rainfall [21], are critical conduits for focused recharge [12] also known as transmission loss in stream hydrology [22]. During flow events, infiltration through the streambed or banks depends on local geology and sedimentary structure [23, 24]. Sediment properties such as grain size, permeability, and heterogeneity strongly influence recharge [25]. Coarse alluvium promotes infiltration [26], whereas fine or clay-rich deposits inhibit it, causing run-off and minimal recharge [27]. Subsurface redistribution of infiltrated water can sustain surface flow [28], controlled by alluvial hydrogeology [25]. While conceptually well understood, these processes remain poorly quantified and rarely represented in models.

Modelling ephemeral SW–GW interactions requires accounting for transient flow, streambed heterogeneity, and non-linear vadose zone dynamics. Xie *et al* [29] and Wang *et al* [30] highlight the formation of an inverted water table—a transient saturated zone beneath streams—driven by rapid infiltration, which is sensitive to geometry and anisotropy [31]. The connected–transitional–disconnected framework by Brunner *et al* [32] is widely used but simplified. Irvine *et al* [33] and Schilling *et al* [34] show that streambed heterogeneity can produce coexisting saturated and unsaturated zones, a concept first introduced by Hodnett and Bell [35]. Quichimbo *et al* [36] demonstrate that GW feedback to the stream can occur even under initially unsaturated conditions, challenging the binary 'connected/disconnected' paradigm. Field and modelling studies confirm that transient infiltration differs fundamentally from steady-state assumptions [37, 38], yet many models still simplify streambed processes and neglect multi-scale flow dynamics.

In African drylands, most infiltrated rainfall is lost to ET by deep-rooted vegetation before reaching the water table. In the Lake Chad Basin, soil moisture is largely governed by surface evaporation and root-zone transpiration [39], while in the *fynbos* ecosystems of South Africa, deep-rooted plants substantially reduce recharge [40]. Conversely, intense rainfall and moderate tree cover can enhance preferential flow and promote localised recharge [41]. In the Limpopo Basin, recharge occurs mainly through episodic river flows rather than diffuse percolation [16]. Overall, ET is a dominant sink, restricting recharge to infrequent high-intensity events. This pattern is consistent with global evidence that vegetation structure and rooting depth strongly constrain recharge, with forested systems exhibiting the lowest recharge relative to rainfall due to high transpiration demands [42].

ET also plays a critical yet under-represented role in ephemeral SW–GW systems. In-channel phreatophytic vegetation can intensify moisture deficits directly beneath streambeds, where focused recharge initiates. Guay *et al* [43] included ET in a quasi-2D model but did not fully couple it with surface flow. Soil–vegetation–atmosphere models (e.g. [44]) treat ET as a key control on soil moisture and recharge, whereas others omit it entirely (e.g. [37]). Field studies observe ET effects [45], and recent work shows ET losses can influence GW feedbacks during flow events [36], yet few models integrate this process. Quichimbo *et al* [46] developed a catchment-scale model simulating ET, run-off, and focused recharge, but temporal linkages among these processes remain under-explored. Understanding ET's modulation of transient infiltration is essential for improving recharge projections in drylands.

Recharge is often estimated using simplified rainfall–recharge functions with thresholds [3, 47] or conceptual models of non-linear vadose zone processes [22, 32]. However, uncertainties in subsurface properties hinder the development of transferable relationships between streamflow and recharge. Here, we propose that focused recharge in drylands with thick vadose zones is not driven by isolated large events, but by clusters of low- to medium-magnitude flows occurring in close succession. We use a unique hydrogeological dataset from arid Australia, combined with transient 2D unsaturated flow modelling, to test this hypothesis. Our results provide new insights into focused recharge mechanisms that have major implications for predicting GW responses to changing rainfall regimes. Identifying the specific clustering characteristics that enable recharge remains crucial, as these depend on local hydrogeology and ET dynamics.

2. Methodology

2.1. Field site description and hydrological data

Fowlers Gap Creek lies in the arid zone of western New South Wales, Australia (figure 1(A) inset). Detailed site descriptions are provided in the supplementary material and in previous work [27, 48]. GW data were collected from a piezometer transect at the *Fowlers Gap Arid Zone Research Station* (FGAZRS), comprising three installations (FG78, FG79, FG80; figures 1(A) and S1).

Piezometer FG79, located on the southern edge of Fowlers Gap Creek, was screened at 18–21 m depth, where GW depth at the time of drilling in March 2013 was 17 m (figure 1(D)). Heads were monitored using a vented pressure transducer (Level Troll 700H, *In-Situ* Inc., USA) from May 2014–November 2016 to November 2021–November 2024, with a gap due to instrument failure and replacement delays. Creek stage was recorded at 15 min intervals with a bubbler gauge (HS-30 Mark 2, Hydrological Services, Australia) installed in a pool behind a natural rock bar ∼350 m upstream of FG79 (figure 1).

Daily rainfall data were obtained from the nearby Fowlers Gap weather station (Australian Government *Bureau of Meteorology* or BoM, Station No. 046128) within the Fowlers Gap Arid Zone Research Station (FGAZRS) compound of the University of New South Wales. The 1970–2024 record shows a mean annual rainfall of 239.4 mm, with high inter-annual variability (SD: 178.9 mm; range: 30.3–809 mm). Mean annual reference ET (ET_o) is 2098 mm, estimated from daily BoM data (2014–2017) using the *Penman–Monteith* formulation [49]. Daily ET_o maxima were 10–12 mm d^{-1} and minima 1–2 mm d^{-1}.

Our analysis focuses on January 2022–November 2023, when GW monitoring at FG79 captured contrasting responses to two streamflow event types. We also reference earlier observations reported in previous studies, with key findings summarised in the supplementary information.

2.2. Numerical modelling of infiltration and ET

To investigate how streamflow patterns influence focused recharge, we simulated unsaturated flow in a 2D axisymmetric domain (figure 1(C)). The model provides a physics-based framework to test whether temporal clustering of streamflow events can overcome antecedent soil moisture deficits and enable recharge, rather than reproducing catchment-scale GW recession typical of drylands [45]. Our approach builds on Quichimbo *et al* [36], extended to include ET as an outgoing vadose-zone flux.

The model solves *Richards' equation* [50] for transient, variably saturated flow, using a *van Genuchten* water retention function [51] and a *Corey*-type relative permeability relationship. Flow is mass-conserving via *Darcy's law* and implemented in the `PorousFlow` module [52] of the `Multiphysics Object-Oriented Simulation Environment (MOOSE)` [53]. Python and bash scripts (with assistance from AI tools) were used for automation of modelling and post-processing.

The modelling domain represents a 17 m vadose zone above a 10 m saturated layer (figure 1(C); and S8). Alluvial layering (figure 2(D)) is represented by an anisotropic permeability tensor with horizontal conductivity one order of magnitude higher than vertical. Lateral boundaries are no-flow, and a basal pressure-dependent sink simulates one-way drainage to deeper GW, preventing upward flow.

Infiltration is driven by time-varying ponded water depth from observed creek stage (figure 2(A)), applied as a *Cauchy* (i.e. third-type) boundary condition (`PorousFlowPiecewiseLinearSink`). The boundary head varies with measured stage, allowing infiltration fluxes to respond dynamically to pressure gradients between ponded water and subsurface conditions. Infiltration activates only during observed surface flow, with mesh refinement resolving steep gradients near the channel.

ET at Fowlers Gap is dominated by River Red Gums (*Eucalyptus camaldulensis*) along creek banks

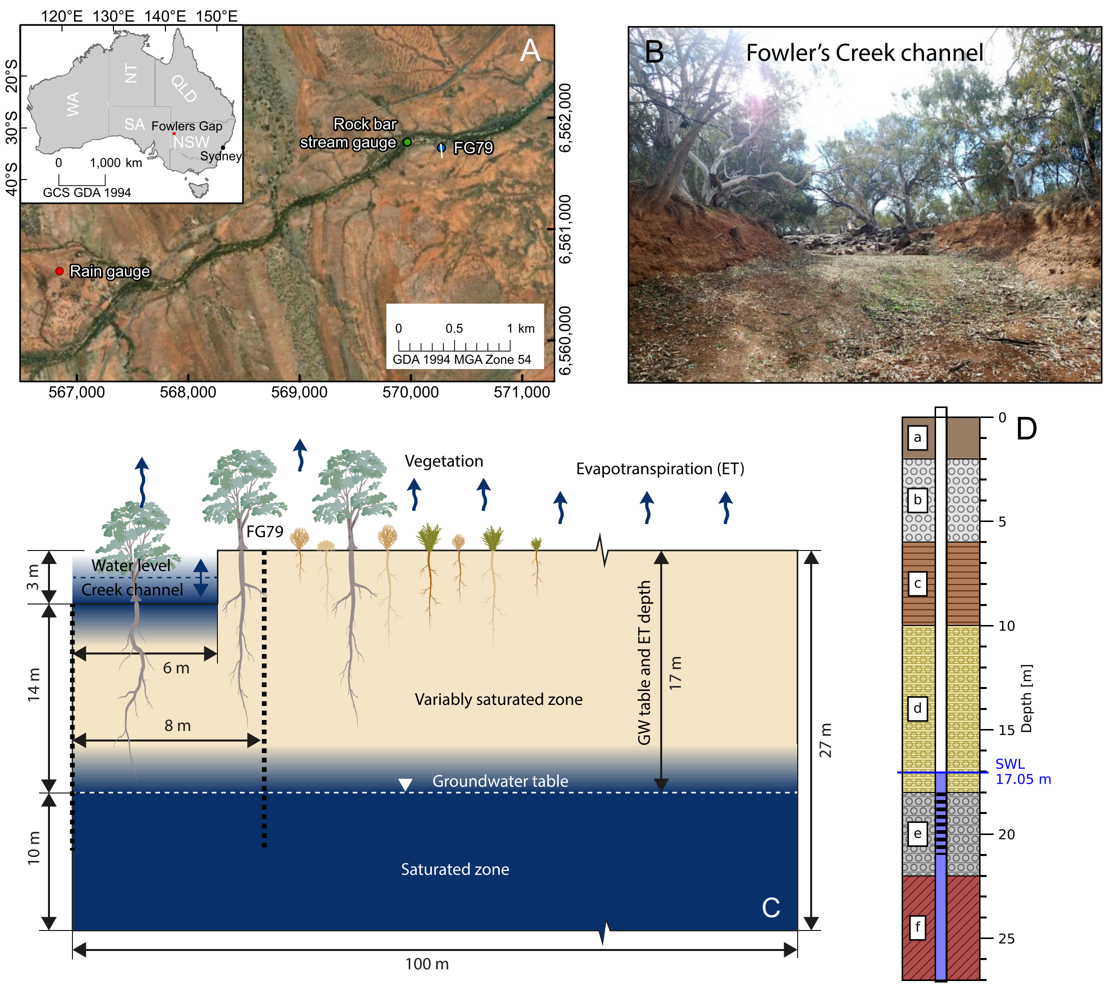

Figure 1. (A) Map of the Fowlers Gap field site within the arid zone of New South Wales (NSW) in Australia (red dot in insert map). The white line near FG79 represents the modelling transect. (B) Dry Fowlers Gap Creek with River Red Gums (*Eucalyptus camaldulensis*) growing along the banks and directly within the channel bed (see figure S2). (C) Conceptual model used for numerical simulations. Horizontal dashed lines within the creek and groundwater depict that these can be time variable depending on stream flow and groundwater recharge. Vertical dashed lines show the location of depth profiles along which results are visualised over time. (D) Piezometer construction details including lithological depth profile obtained during drilling for FG79: (a) topsoil; (b) gravel, large, clay; (c) clay, brown, hard; (d) clay, white with some gravel; (e) gravel, with some clay bands with piezometer screen; (f) clay, red gray.

and within the channel bed (figures 1(B) and S2). These phreatophytic trees access rainfall, flood-recharged soil moisture, and GW, maintaining transpiration for years after inundation [54]. Isotopic evidence shows that they shift from surface to subsurface water sources as ephemeral flows cease [55]. Their dense canopies suggest reliable access to deep subsurface moisture, consistent with field observations of deep rooting depths [56] in our case, approaching the 17 m-deep water table (T. Doody, pers. comm., 2025). These processes underpin the need to include ET as a dynamic control on vadose-zone water fluxes.

ET is represented using a depth-limited root-uptake sink (`PorousFlowHalfCubicSink`) applied throughout the 17 m vadose zone beneath both the creek and riparian surfaces. The sink is scaled by daily reference ET ($ET_0 \approx 2100\,\mathrm{mm\,yr^{-1}}$) from the weather station, providing the upper bound on potential transpiration [54, 57]. Moisture stress is captured via a cubic pressure-head function that progressively reduces flux as the profile dries, consistent with stomatal regulation and sapwood contraction in River Red Gum [54]. Rooting depth and moisture stress therefore act together: uptake is permitted down to 17 m but is curtailed locally when pressures fall below the stress threshold. Fluxes are also weighted by relative permeability and viscosity, enabling simulation of both shallow post-flood uptake and deeper GW extraction—characteristic behaviours of River Red Gum systems [55, 58]. Conceptual and mathematical details are provided in the supplementary material.

The modelling period spans 21 November 2021–6 June 2023 (563 d), covering multiple streamflow and dry intervals. Prior to this period, no surface flow had occurred since June 2021. The model starts from physically realistic hydrostatic initial conditions

Table 1. Overview of sediment and water properties used for variably saturated numerical modelling of stream infiltration and water percolation.

Parameter	Symbol	Unit	Value
Porosity	ϕ	—	0.15
Horizontal hydraulic conductivity	K_h	$m\,s^{-1}$	2.3×10^{-6}
Vertical hydraulic conductivity	K_v	$m\,s^{-1}$	2.3×10^{-7}
van Genuchten exponent	m	—	0.5
van Genuchten α	α	m^{-1}	5.9
Residual saturation	S_r	—	0.05
Relative permeability exponent	n_k	—	2
Water density	ρ_w	$kg\,m^{-3}$	1000
Water viscosity	μ_w	Pa·s	1×10^{-3}
Water bulk modulus	$K_{f,w}$	GPa	2.2

and includes a spin-up phase incorporating multiple observed flow events before results are interpreted, allowing antecedent moisture conditions to develop dynamically throughout the vadose zone. A total of 5012 adaptive time steps were taken, with a minimum step size of 15 min during rapid stage changes and a maximum of 1 d during extended dry periods. The analysis focuses on a major flood followed by a cluster of smaller flows, which together produced contrasting recharge responses.

Diffuse rainfall infiltration is excluded, consistent with field evidence showing rapid run-off and negligible direct infiltration in this catchment [27]. Hydraulic conductivity, porosity, and *van Genuchten* parameters were selected within ranges typical of semi-arid alluvium [59] and adjusted within plausible bounds to reproduce observed infiltration and GW responses. The goal was not calibration, but to test whether clustered flow events can generate recharge through a thick vadose zone under physically realistic conditions. Model parameters are listed in table 1, with sensitivity tests in the supplementary material. Outputs include time series of saturation, pore pressure, hydraulic head, depth-resolved saturation beneath the streambed, and water-table elevation.

3. Results

3.1. Field observations of GW recharge

Figure 2 presents observations from the rain gauge, calculated ET (ET_o), stream stage, and GW levels in piezometer FG79 between January 2022 and the end of 2023. ET_o shows a strong seasonal pattern, ranging between 0.8 and 16.1 mm d^{-1} (figure 2(A)). Stream flows generally show a sharp rise following precipitation and run-off, followed by a rapid fall and slower recession (figure 2(B)). The cease-to-flow elevation at the upstream rock bar is at 163.5 mAHD (meters above Australian Height Datum). Stream levels above this indicate active flow, while levels below reflect isolated pools retained in local depressions or a completely dry streambed, consistent with conceptual models of dryland stream-GW interactions [28].

In April 2022, a major single flood event (80.8 mm rain over 10 h was recorded on 26 April at the Rock Bar Climate Station) caused stream levels adjacent to FG79 to briefly reach 2.73 m. During this event, the pressure transducer in FG79 recorded a brief but pronounced rise in water level within the thin aquifer, consistent with overtopping and flow down the inside of the piezometer (figures S4 and S7). However, the flood did not produce a rise in the water table from infiltration through the streambed, which would have led to a much longer response. It is noted that previous floods in the year 2000 (figure S5) and 2015 ([48]; figure S6) exhibited a similar response.

Between October and December 2022, several moderate rainfall events (daily totals of 20–30 mm with 278 mm over 141 d) generated a series of streamflow peaks (0.5–1.73 m). These events formed a temporally clustered sequence of medium flow events rather than a single high-magnitude flood. During much of this time, stream levels remained above the cease-to-flow elevation at the gauge, indicating continuous surface flow past FG79. The GW level began rising after the third stream flow peak, increasing from 147.2 m AHD through a first small peak to a second with a maximum of 149.5 m AHD, before reaching a level of 148.3 m AHD approx. 1.1 m higher than before the events (figure 2(C)). GW observations to the end of 2024 indicate that GW levels remained fairly constant after the recharge period (figure S4).

Notably, the response in October 2022 was triggered, *not* by a single large flood (as in April 2022), but by multiple moderate magnitude events occurring in close succession (September 2022–January 2023). The subsurface behaviour is consistent with infiltration and percolation from the stream forming a water table mound beneath the channel [22]. The gradual decline following the peak suggests lateral GW flow away from the stream [45]. The increased level indicates that storage at 18–21 m depth (figures 1(D) and S2) had been replenished through focused GW recharge from the stream channel. The increased level at FG79 has been maintained for nearly 2 years after the recharge event, but will probably begin decaying in response to ET_o in the future. It is noted however, that the climate in 2024 has been relatively wet (345.6 mm rain, approx. 105 mm above average) with possibly sufficient percolation to the vadose zone that the *Eucalyptus camaldulensis* have not had to draw water from the water table below [54].

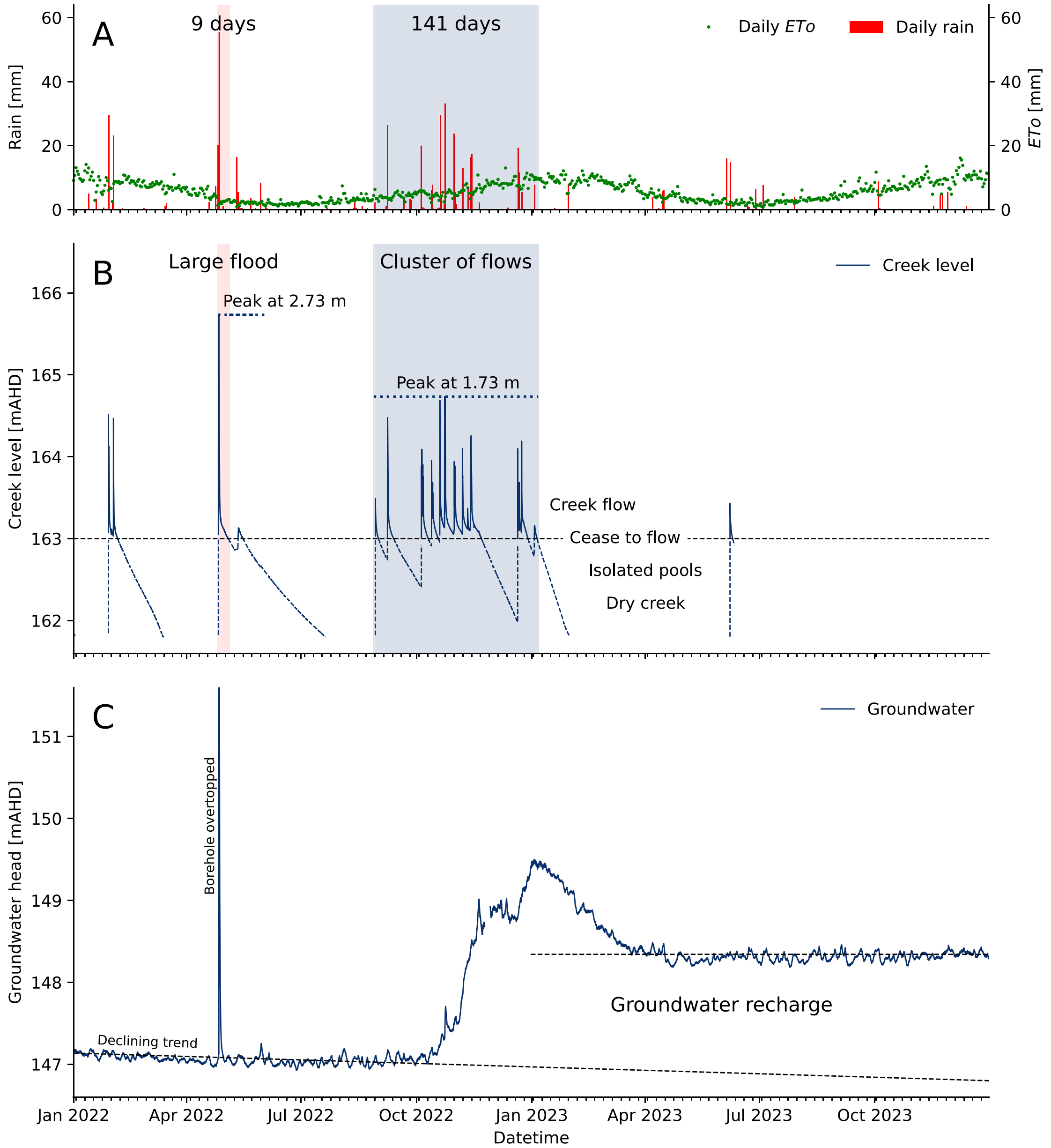

Figure 2. (A) Daily rainfall and evapotranspiration as measured at the rain gauge (figure 1(A)). The total and average values over the respective time periods: the single flood (9 d) total of 80.8 mm of rainfall falling in only an 8 h period at the Rock Bar gauge; and 21 mm of reference ET_o, with daily averages of 2.3 mm d^{-1} and 2.6 mm d^{-1}, respectively; the flow cluster (141 d) 278 mm of rainfall and 865.2 mm of ET_o, with daily averages of 2 mm d^{-1} and 6.1 mm d^{-1}, respectively. (B) Fowlers Gap Creek surface water level response as measured at the Rock bar site (figure 1(A)). The monitoring equipment at the Rock bar site failed in July 2023. (C) Groundwater heads in piezometer FG79 adjacent to the creek showing no recharge response (but some water added due to piezometer overtopping) to a large flood and a clear recharge response to a cluster of closely occurring moderate-sized flow events. The rising head indicates groundwater mounding underneath the stream followed by lateral groundwater flow due to the head gradients caused by infiltration [45]. *Y* axes for both stream and groundwater have the same scale for visual comparison of magnitudes.

3.2. Numerical modelling of vadose zone processes

Figure 3 shows the modelled vadose zone moisture evolution caused by the single flood and the cluster of moderate flow events, as shown in figure 2(B). The modelling results are provided for two locations: (1) directly underneath the stream centreline (figure 3(B)) and (2) at a distance of approximately 2 m from the bank, representing the GW level measurements (figure 3(C)). The initial spin-up period is excluded, but can be seen in figure S9. Generally, the vadose zone is filled with water infiltrating during the flood, with downward percolation slowing exponentially over time.

Results from the single flood (i.e. large flood) indicate that most of the water that infiltrated (the majority was lost as run-off) remained within the vadose zone, compensating for the pre-existing moisture deficit; it may have reached the tension-saturated zone but did not recharge the water table. In contrast, multiple closely spaced flow events (i.e. cluster of flows) sequentially increase saturation, eliminating the moisture deficit within the vadose zone. This

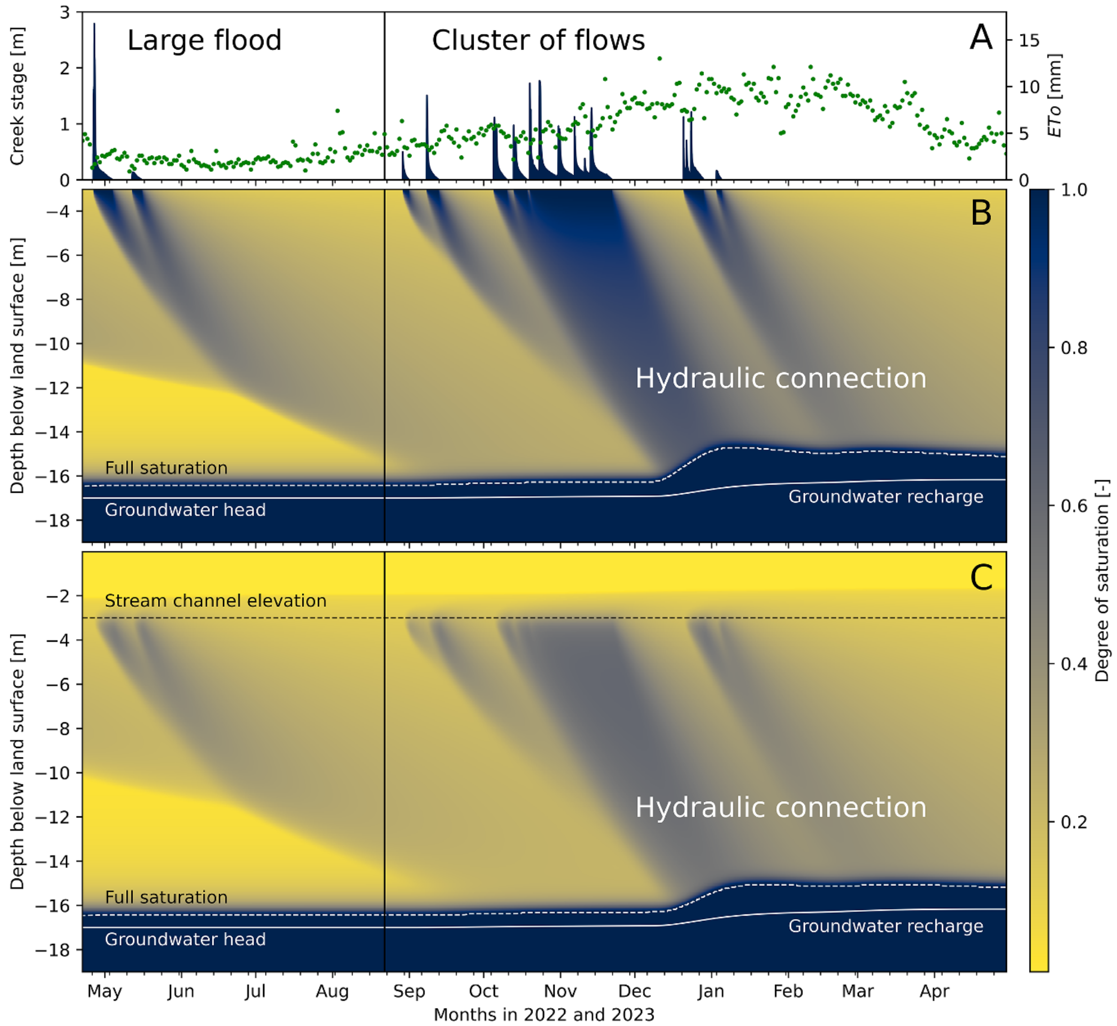

Figure 3. Modelled temporal evolution of infiltration and groundwater recharge during a single large flood and a cluster of moderate-magnitude flows. (A) Creek stage (water depth above the streambed) for both flow types, plotted only when flow exceeds the cease-to-flow threshold. Green dots show daily reference evapotranspiration (ET_o) from the weather station (figure 1(A)), used to scale transpiration by riparian and in-channel River Red Gums (see figure S2). (B), (C) Simulated degree of saturation (colour shading) with time (x-axis) and depth below the streambed (y-axis). Darker tones indicate higher saturation. Curved, gradational bands sloping to the right represent the downward advance of the wetting front through the vadose zone. Each successive flow event increases saturation, non-linearly enhances hydraulic conductivity, and accelerates vertical percolation. (B) Shows conditions directly beneath the streambed centreline; (C) corresponds to the piezometer location indicated in figure 1(C). Repeated flow events progressively overcome evapotranspiration-driven soil-moisture deficits, eventually creating a continuous hydraulic connection between the streambed and the water table. This transition marks the onset of gravity-driven percolation and groundwater recharge. The initial spin-up period is omitted here for clarity but is shown in figure S9.

raises the relative hydraulic conductivity and enables faster downward movement of water during subsequent events. As a result, the GW level rises approx. 0.83 m (figure 3(C)), consistent with field observations (figure 2(C)). The model appropriately captures this response, including the double peak associated with a sub-cluster within the main flow cluster. The contrast between the large flood and cluster of flows emerges naturally from our continuous simulation, reflecting the observations from our field dataset.

4. Discussion and conclusions

Over a decade of GW monitoring showed that even large floods overtopping piezometers—January 2015 (166 mm over 47 h; 3.56 m peak: figure S5), March 2020 (66.2 mm over 23 h; 3.71 m: figure S6), and April 2022 (80.8 mm over 8 h; 2.73 m: figure S7)—did not produce a measurable GW response (figures 2 and S4). Despite their magnitude, these events failed to initiate recharge: most floodwater was lost as run-off, while infiltrated water was retained in the vadose zone and later removed by ET. These observations agree with Acworth *et al* [27], who showed that run-off can begin within 10 min of rainfall onset, leaving little opportunity for surface retention or local infiltration.

Focused recharge occurred only during a period of multiple clustered low- to moderate-magnitude flows, demonstrating that *temporal clustering* is essential for recharge in drylands with thick vadose zones. Clustering enables progressive wetting, overcoming

ET-induced moisture deficits. As saturation increases, hydraulic conductivity rises non-linearly (e.g. [59, 60]), forming a transient high-conductivity pathway between stream and aquifer. Isolated floods, even large ones, rarely persist long enough to overcome dry antecedent conditions. Closely spaced events maintain residual moisture, elevate conductivity, and accelerate percolation, whereas intervening ET reverses this process. Successful recharge therefore depends jointly on the time required to wet the vadose zone and shorter intervals between events that prevents complete drying.

Our simulations provide a conceptual test of this mechanism rather than a calibrated reproduction of field conditions, isolating the process by which clustered flows enable recharge. The difference between the magnitude and timing of field observations and modelling results is likely due to spatial heterogeneity of the hydraulic properties present at the field site. However, the critical control on focussed GW recharge is the duration and sequencing of surface flow events rather than their magnitude. Temporal clustering sustains the presence of water in channel sediments, lengthening infiltration times until a hydraulic connection with the GW develops—consistent with findings from other drylands where flow duration governs recharge efficiency (e.g. [61]).

The October 2022 recharge event was the only one observed during a decade of monitoring. A minor recession break noted by Acworth *et al* [48] after the 2015 flood likely reflects a similar cluster of streamflows in 2016 (figure S14), further supporting this interpretation. Despite nearly 300 mm of rainfall during the 2016 season, field evidence indicates that diffuse recharge did not occur. Boreholes intersecting basement rock (e.g. FG80) remained dry throughout multi-year monitoring, while nearby alluvial piezometers (e.g. FG79) responded to clustered flow events. In the upper Fowlers Gap catchment, runoff begins within minutes of rainfall onset [27], confirming negligible GW recharge beyond the creek. These observations demonstrate that GW recharge is restricted to focused infiltration through the ephemeral streambed.

A major contribution of this study is demonstrating—through direct aquifer data and process-based modelling—that focused recharge beneath ephemeral streambeds is governed primarily by *event sequencing and flow duration*, not flood magnitude. While ET's limiting role on diffuse recharge is well recognised (e.g. [57]), most recharge studies in ephemeral streams have either neglected ET [36, 38] or assumed that large floods suffice to overcome moisture deficits [47]. By incorporating ET to depth, our model captures the basic biophysical feedbacks of drying and re-wetting: between isolated events, sediments desiccate through ET, and only successive flows re-wet the profile sufficiently to raise relative hydraulic conductivity and permit percolation (figures 3(B) and (C)). This balance between evaporative loss and cumulative wetting explains the threshold-like nature of recharge.

Explicitly resolving these vadose-zone feedbacks in the model enables assessment of the spatio-temporal evolution of saturation and highlights the non-linear controls governing focused recharge. The observed long-term GW decline (approx. 0.3 m yr^{-1} from 2014 to 2022; figure S4) and its abrupt stabilisation following the 2022 cluster event indicate variable vegetation–GW coupling depending on water availability. Deep-rooted vegetation regulates vadose-zone moisture primarily through transpiration, drying sediments between events and thereby setting recharge thresholds. This behaviour is consistent with global analyses showing that vegetation structure, rooting depth, and transpiration intensity strongly constrain recharge magnitude across climates, with woody ecosystems exhibiting particularly low recharge rates [42].

It is also recognised that deep-rooted vegetation can redistribute water within the vadose zone via hydraulic redistribution, whereby water taken up from wetter deep layers is passively released into drier shallow soils during periods of low transpiration demand. Field studies using isotopic tracers demonstrate that this process enhances shallow soil moisture but remains largely confined to the root zone [62, 63], while modelling work shows that its magnitude depends on rooting architecture, soil texture contrasts, and root hydraulic conductance [64]. Recent syntheses emphasise its role in buffering drought stress rather than generating GW recharge in the absence of sustained surface-water inputs [65]. In this context, hydraulic redistribution may modulate antecedent vadose-zone conditions and warrants further investigation; however, it does not alter the principal mechanism identified here, whereby temporally clustered surface flows progressively wet the vadose zone to a point beyond which focused recharge is enabled.

The model results also show that the magnitude and timing of recharge are highly dependent on vadose-zone hydraulic properties (see figures S10–S13). Hydraulic conductivity governs the propagation of flow, porosity controls storage, and together they determine how effective surface flow clustering is in controlling recharge. Coarser or more permeable sediments require less clustering; finer or clay-rich profiles demand longer or denser flow sequences. Depth to GW modifies this threshold: shallow water tables reconnect more readily, whereas thick vadose zones, like at Fowlers Gap, require sustained wetting. Vegetation structure also matters, with deep-rooted phreatophytes delaying recharge by extracting moisture from depth, while sparse or shallow-rooted vegetation allows faster re-wetting. Although these factors alter magnitude and timing, the underlying mechanism of progressive wetting overcoming ET-driven drying should remain broadly transferable across drylands. Testing this across gradients in texture, depth, and vegetation will clarify how clustering controls recharge for individual local contexts.

Earlier work from semi-arid southern Africa linked GW recharge to prolonged wet periods or large cumulative rainfall totals, leading to practical rules of thumb for recharge estimation, but without resolving whether recharge resulted from isolated extreme events or from the temporal clustering of successive flows (e.g. [19, 20]). More broadly, dryland recharge is often attributed to extreme rainfall events (e.g. [3, 66, 67]), with infiltration frequently equated to recharge in the absence of direct aquifer evidence. While extreme rainfall has been shown to produce recharge in some settings (e.g. [3, 67]), many studies rely on coarse rainfall aggregation (e.g. monthly totals), obscuring whether recharge arises from single extremes or temporally clustered events. Our findings show that resolving event timing is essential for understanding threshold behaviour in dryland recharge.

The future of recharge from ephemeral and intermittent flows under climate change will depend on shifts in rainfall timing and intensity. Long-term records and projections for drylands, including Fowlers Gap, indicate increasing rainfall intensity but not necessarily greater frequency or clustering. Acworth *et al* [27] report a ∼200% rise in rainfall intensity and ∼60% increase in sub-hourly peaks, consistent with broader hydrological intensification [14]. Yet such intensification often enhances run-off rather than recharge when antecedent soil moisture is low. Hence, changes towards short, intense, or isolated floods are unlikely to sustain recharge in thick-vadose-zone environments. Climate models project fewer wet days, longer dry spells, and shorter, fragmented wet periods [15], while global models still underestimate extremes [68]. In such settings, recharge depends on temporal clustering rather than episodic large floods—a process difficult to resolve in current projections.

Overall, our results show that vadose-zone processes must be explicitly represented when linking rainfall to focused GW recharge. Recharge arises from non-linear interactions among vadose-zone structure, hydraulic properties, and flow event sequencing. It is governed not by total rainfall or average intensity, but by whether successive rainfall–run-off events occur closely enough to sustain infiltration and offset evaporative losses. These insights can also inform managed aquifer recharge using dry stream channels: maintaining or engineering longer infiltration periods, rather than short high-intensity pulses, can markedly improve recharge efficiency in arid regions. Over nearly a decade of observation in Fowlers Gap Creek, recharge occurred only once—during a clustered sequence of flows in late 2022—highlighting the episodic and rare occurrence of recharge in these environments.

Understanding the role of streamflow clustering is thus critical for resolving the threshold-driven character of recharge in arid and semi-arid regions. Conventional approaches based on mean rainfall trends are insufficient; process-based and event-scale modelling frameworks are required, integrating hydrogeological properties and rainfall-clustering metrics. Future work should quantify how climate-driven changes in storm sequencing and vegetation water use (e.g. [69]) alter ET and recharge thresholds. Together, these findings emphasise the need for improved process-based recharge modelling in drylands and their importance for water security and governance under ongoing climatic and environmental change [7], but also emphasises the need for long-term monitoring to provide real observations relevant to the local context.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.6084/m9.figshare.30866627 [70].

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