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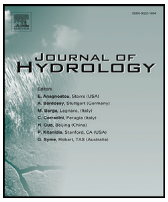

Research papers

Nonstationary recharge responses to a drying climate in the Gnangara Groundwater System, Western Australia

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ABSTRACT

The response of groundwater recharge to climate change needs to be understood to enable sustainable management of groundwater systems today and in the future, yet observations of recharge over long-enough time periods to reveal responses to climate trends are scarce. Here we present a meta-analysis of 60 years of recharge studies over the Gnangara Groundwater System of South-West Western Australia, covering a period of sustained drying consistent with climate change projections. The recharge process in the area is defined by a wet winter during which rain saturates a deep, highly permeable soil profile with very low water storage capacity. Measurements of recharge since the 1960s show near-linear reductions in potential recharge of 50%, in response to a 20% reduction in rainfall. For the best-represented land cover in the dataset (Banksia woodland), the reduction in potential recharge was closer to 70%. A simple analytical model suggests that reductions in the duration of winter, coupled with a decreased frequency of winter storms, were most responsible for these declines, and reveals the potential for nonlinear relationships between the recharge fraction (recharge/precipitation) and climatic variables such as mean storm frequency, mean storm depth, and the length of the winter wet season. Overall, results suggest that recharge declines in drying Mediterranean groundwater systems are likely to outstrip the declines in rainfall, and that leveraging existing observation networks worldwide to characterise recharge responses to changing climate is needed to overcome existing interpretation challenges created by inconsistent sites, methods and durations of recharge estimation.

1. Introduction

Groundwater is the largest source of liquid freshwater on Earth (Gleeson et al., 2016), providing an estimated 1000 km^3/yr of water supply, 70% of all irrigation water used globally (Gleeson et al., 2016), and large fractions of domestic water supply worldwide (e.g. Carrard et al., 2019; DeSimone et al., 2015; Daly, 2009). Some 10%–30% of global groundwater use is non-renewable (Bierkens and Wada, 2019), in that the water stores used cannot be replenished by natural recharge processes over human lifetimes. The remainder of groundwater used is ‘modern’ and was recharged in the last 50 years (Gleeson et al., 2016). Given appropriate management, modern groundwater is a renewable water source. The sustainable use of modern groundwater requires the essential understanding of recharge: a pressing challenge as climate change alters patterns of rainfall.

Recharge is difficult to measure and its magnitude and distribution remain globally uncertain (Taylor et al., 2013). Data at global scales are too sparse to enable interpretation of recharge responses to climate change (Moeck et al., 2020). Conversely, on regional scales, the sensitivity of recharge rates to climate and land use change is well documented (Scanlon et al., 2006). Tracer and tree-ring datasets show that recharge rates co-vary with drought over centuries (Manna et al., 2019), while tritium and chemical tracers show deep percolation responding to rainfall on decadal scales (Verhagen et al., 1979; Edmunds et al., 1992; Cook et al., 1992; Priestley et al., 2023). Water table hydrographs reveal that episodic recharge is sensitive to changes in rainfall intensity (Zhang et al., 2016; Thomas et al., 2016), and demonstrate the complexity of relationships between recharge rates

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and climatic or environmental factors. For example, in South-Eastern Australia, changes in rainfall seasonality could reduce recharge even if total annual rainfall was constant, and falling groundwater depths could reduce recharge over time (Fu et al., 2019).

Most of the empirical studies cited, however, rely on correlative relations between inferred recharge rates and climatic drivers. Such correlative relationships omit process insights. Because changes in land surface and vadose zone processes can amplify the impact of climatic changes on recharge, there is a need to link recharge observations with recharge process insights to interpret potential recharge responses to changing climate.

Here we make the connection between observations, process and theory to explore changes to recharge over the Gnangara groundwater system of the Swan Coastal Plain in south-west Western Australia, a region that has experienced a 15% decline in annual rainfall consistent with anthropogenic climatic heating since the 1970s (State, 2022). This area was identified by the 2007 IPCC report to be a hotspot for its predisposition to be adversely affected by changing climate (Hennessy et al., 2007)

The study contains three parts:

- A synthesis of the literature, field observations and experiments, used to conceptualise the recharge process and identify process knowledge gaps.
- A meta-analysis of data from 34 recharge studies on the Gnangara groundwater system over the past 50 years.
- A simple dynamic model of recharge based on the process conceptualisation outlined in part 1.

The synthesis of recharge processes is illustrated and corroborated with data from the intensively monitored *Gingin Terrestrial Ecosystem Research Network (TERN) Processes* site (Silberstein, 2015; Beringer et al., 2016). We separated the results of the synthesis into three sections: *canopy and soil surface* processes, *unsaturated zone* processes and *saturated zone* processes. (See Section 6.1 and therein subsections). The history of recharge studies covering the period of observed climatic drying, and the meta-analysis of studies showing the recharge nonstationarity are presented in Section 6.2. By focusing on a 60-year period of known drying, the study window is large enough to identify recharge responses to long-term trends. Although other anthropogenic factors, in particular land cover change, have impacted the study area, we addressed those in the study design by controlling for land cover, and avoiding areas of significant pumping activity. Finally, the simple model is used to explore the response of recharge to changes in climate drivers and the sensitivity of recharge to these changes in different landscape settings (See Section 6.3).

2. Study area

2.1. The Gnangara groundwater system

The Swan Coastal Plain lies in south-west corner of Australia, bounded between the Indian Ocean and the ancient Yilgarn Craton in the east (Hocking et al., 1994). It comprises north-south oriented dune-swale sequences, crossed by river systems flowing east to west, with a range of land uses including the sprawling Perth metropolitan area, agriculture, natural and plantation vegetation (see Fig. 1). Local surface drainage, however, is mostly absent due to the highly permeable sands.

The region experiences a hot Mediterranean climate, with potential evaporation exceeding rainfall, the only source of precipitation in the region, for 9 months a year (Australian Bureau of Meteorology, 2016b,c). Average rainfall for 1993–2021 was 730 mm/year (Australian Bureau of Meteorology, 2021), and average annual pan evaporation approximately 1800 mm (Australian Bureau of Meteorology, 2016b) (Bureau of Meteorology station n. 9021). The largest rainfall events arrive as winter cold fronts, with several events each year exceeding 25 mm/day, and around 75 rainy days per year (Australian Bureau of Meteorology, 2016a).

Three freshwater groundwater aquifers are identified in the region - an unconfined “superficial” aquifer, the confined Leederville aquifer, and below that, the deep, ancient, Yaragadee aquifer (Meredith et al., 2012). The superficial aquifer consists of Quaternary sediments. Near the coast are young (<10 000 years before present, ybp) calcareous sands called the Quindalup Formation. The Spearwood Formation, consisting of older (≈50,000 ybp) partly leached sands and limestone lies further inland. Further inland, old (up to 100,000 ybp) highly leached sands in the Bassendean Formation abut colluvial clays in the Pinjarra and Yanga formations, forming the eastern margin of the coastal plain (Davidson, 1995a), see Fig. 1. The superficial aquifer is exposed as numerous groundwater dependent lakes and wetlands (Froend et al., 2016; Semeniuk and Semeniuk, 2006), supports stygofauna and troglofauna communities (Western Australian Environmental Protection Authority, 2012) and recharges the underlying confined aquifer systems. Although specialised recharge and discharge processes from the superficial aquifer occur within limestone formations and near surface water systems and wetlands, recharge on the Swan Coastal Plain is dominated by diffuse recharge on the extensive sands.

Climate change impacts on water balance are apparent in the region. Mean annual temperatures increased by 1 °C since the early 20th century, with associated increases in the duration and temperature of hot spells, but little change in measured pan evaporation (Sudmeyer et al., 2016). A pronounced declining trend in rainfall began in the late 1960s. A 15% reduction in annual rainfall has occurred in the region since 1970 (see Fig. 3), causing much larger reductions in streamflow and surface water resources (Petrone et al., 2010; Hughes et al., 2012; Kinal and Stoneman, 2012). From 2010–2020, inflow to water supply dams was 17% of the 1911–1974 average (Water Corporation of Western Australia, 2021a), implying an 83% reduction in surface flow. The drying climate prompted changes in water supply, particularly to the growing population of Perth: surface water resources supplied 88% of drinking water in the 1960s, by 2000 groundwater supplied 60% of drinking water, and in 2023 ocean desalination and groundwater each supply ≈40% of the drinking water for the city (Water Corporation of Western Australia, 2021b). In the study area, groundwater is used for irrigated agriculture, rural water supplies, and private garden and public open space irrigation for the city. Historically, most of this groundwater has been abstracted from the superficial aquifer, which provided up to 4.5 times more water than the deeper formations (Department of Water, 2009). As shown in Fig. 1 panel C, which shows the elevation of the water table at the GB15 a bore located in the Banksia woodland north of Perth, growing abstraction and the declining rainfall trend coincide with a sustained decline in the level of the superficial aquifer. Land use and water allocation planning, have aimed to stabilise the level of the superficial aquifer to protect both water resources and the biodiversity they sustain. Adapting these changes to account for the drying climate is an urgent issue. Some 250 km south of the study area, recent analysis of speleotherms and cave drip waters suggest pronounced reductions in recharge have also occurred in response to drying, with contemporary recharge rates being unprecedentedly lower than they have been for at least 800 years. Priestley et al. (2023). As yet, no equivalent understanding has been obtained for the Gnangara groundwater area.

2.2. The Gingin TERN-Ecosystem Process site

The *Gingin TERN-Ecosystem Processes* site (Beringer et al., 2022) is an intensively instrumented research site located on coarse, deep and hydrophobic Bassendean Sands in a Banksia woodland ecosystem overlying the Gnangara groundwater mound. Established to constrain estimates of recharge to the Gnangara mound (Silberstein, 2015), the Gingin site is part of Australia’s National Collaborative Research Infrastructure Strategy (NCRIS) TERN program. Since 2011 it has measured

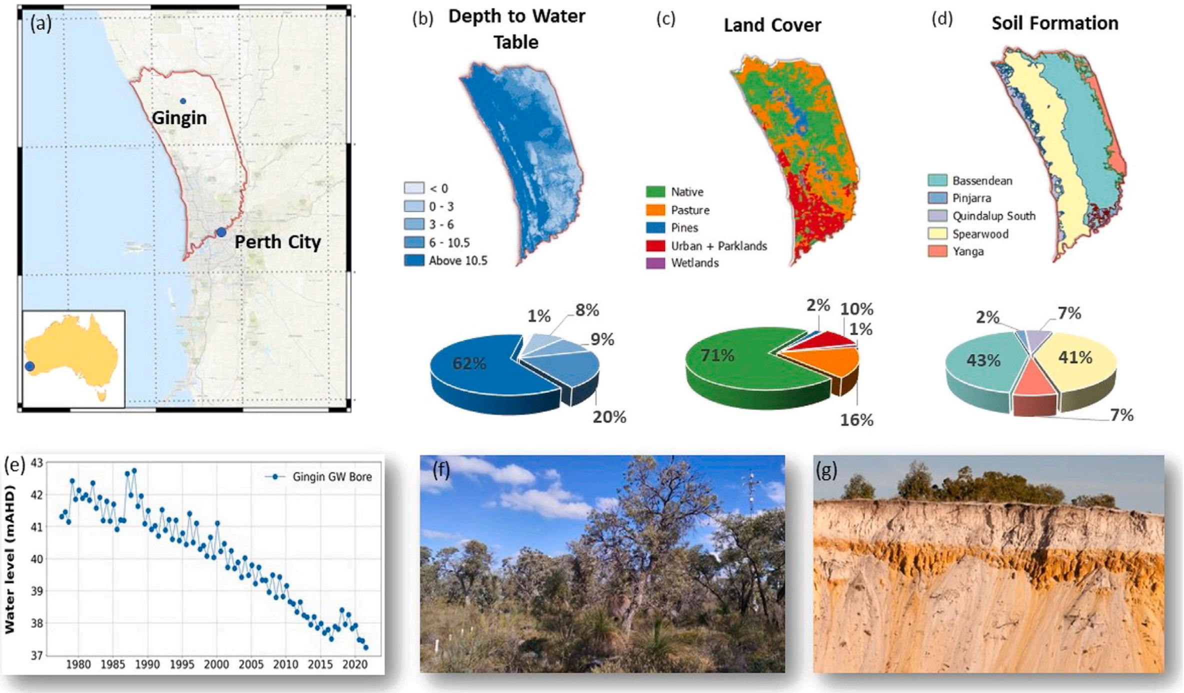

Fig. 1. Study area and important geographical features. (a) The study area is the region associated with the Gnangara Groundwater Mound, north of Perth in Western Australia. The region exhibits considerable variety in (b) depth to groundwater, (c) land cover, (d) and soil formations. Of the formations shown, the Bassendean, Spearwood and Quindalup are aeolian dune formations, while the Pinjarra and Yanga are mostly clay. (e) shows the decline in water level near the Gingin OzFlux site, (Department of Water and Environmental Regulation Bore GB15, −31.3765N, 15.7144E), (f) shows the native (i.e. Banksia) vegetation and (g) the typical sandy soil profile (modified from Wikimedia.org CC BY 2.5 AU DEED).

water, carbon and energy fluxes using an eddy covariance system, four vertical soil moisture arrays, 10 piezometers, two throughfall arrays and a weather station (see Fig. 2). Data from the site are available at https://www.ozflux.org.au/.

Throughout this study, we illustrate the recharge process and climate trends with data from the Gingin site, and data from nearby long-term weather gauges (Gingin Townsite, Bureau of Meteorology station 009018). We also present additional data collected by the authors at the Gingin site including soil hydraulic analyses from 5 soil samples taken at depths of 1 m, 1.5 m, 2 m, 4 m, and 7 m depth on the Bassendean Sands at the site, soil wetting profiles, and interception measurements.

3. Synthesis and definitions

3.1. Recharge definition

A variety of terminology is associated with "recharge" (e.g. Bierkens and Wada, 2019), as illustrated in Fig. 2. Recharge fluxes can be reported as potential (gross) recharge, comprising all water that moves through the unsaturated zone and into the water table and groundwater domain. The term deep drainage, which specifically refers to the flux of water moving below plant roots (Petheram et al., 2002), is used interchangeably with potential recharge for steady state, vertical flow conditions (Leaney et al., 2011), most usefully where plants' roots are distant from the water table (Groom, 2004). In contrast to gross or potential recharge, net recharge accounts for loss of water from the water table by evaporation or plant uptake. Over the Gnangara groundwater system, potential recharge is a vertical downward flux originating from rainfall, reduced by evaporative losses from interception, bare soils and plant water in the unsaturated zone. The flat topography and coarse soils result in negligible lateral unsaturated and surface fluxes (Dawes et al., 2012). There can be significant plant water uptake from the capillary fringe and evaporation from shallow water tables, however, so that net recharge may be significantly lower than potential recharge. Both net and potential recharge may be reported in absolute terms as a depth of recharge, or as the recharge fraction, the ratio of recharge to rainfall in that water year.

Over shallow water tables, rainfall may pond and evaporate (Semeniuk and Semeniuk, 2011), with these losses referred to as rejected recharge (Theis, 1940; Anderson et al., 2015). There is little rejected recharge over the Gnangara Groundwater System. Permanently wet environments like rivers or lake beds may produce focused recharge, while diffuse recharge occurs more uniformly and at lower rates. Most recharge in the study area is diffuse.

Recharge may occur persistently in space and time, or it can be heterogeneous or intermittent. In the study area, most fluxes through the vadose zone occur in winter, evaporation rates peak in spring and evaporative demand peaks in summer (Sharma et al., 1991). Thus, seasonal recharge (the winter recharge fluxes) may be used more-or-less synonymously with potential recharge, while the term annual recharge accounts for summer evaporation, and is closer in nature to net recharge (Sharma et al., 1991). The strongly seasonal climate, its high inter-annual variability and the long-term drying trend all point to considerable time-variation in recharge, sometimes referred to as transient recharge, in contrast to constant or steady state recharge. Given the conditions over the Gnangara groundwater system, gross and net diffuse recharge form the focus of this study.

3.2. Definition of climate change responses

Climate change causes rainfall, temperature and evaporation, and fluxes like recharge that depend on them to exhibit long-term trends over time. To distinguish long-term, climate driven trends from other sources variability, it is useful to consider if the statistics of the fluxes are time dependent. For instance, Fig. 3 shows rainfall at the Gingin townsite rain gauge since 1907 (top panel). The annual rainfall (grey dots) shows large variability, masking longer-term trends. Running averages over 5 (red line) and 25 (yellow line) periods are smoother, and

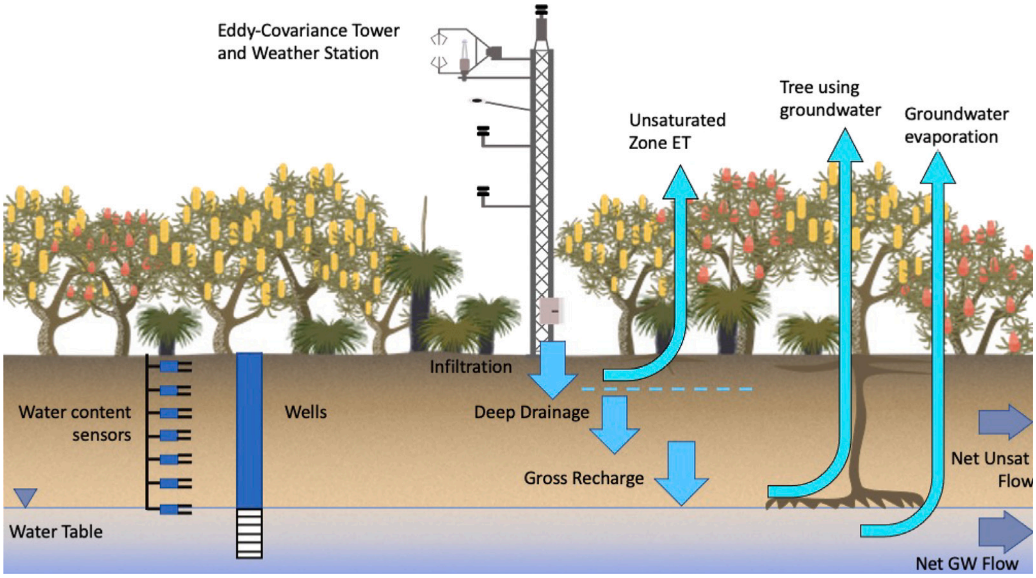

Fig. 2. Schematic illustration of the infrastructure at the *Gingin TERN Ecosystem Processes* site, and of recharge processes occurring at the site and across the Gnangara Groundwater System. The vegetation depicted is a Banksia woodland, with deep-rooted trees and shallow-rooted understorey plants. Instrumentation shown includes an Eddy Covariance Tower, vertically arranged water content sensors and groundwater wells. Straight, pale blue arrows show vertical fluxes of water into the soil (infiltration), below the shallow root zone (deep drainage ≈ infiltration − unsaturated zone evapotranspiration), and to the water table (gross recharge ≈ deep drainage). Vertical water losses due to evaporation and transpiration from both the unsaturated zone and the groundwater are shown with curved light blue arrows. Lateral losses due to net lateral unsaturated flow and groundwater flows are shown with horizontally oriented, dark blue arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reveal that the mean rainfall is declining with time. Time dependence in the statistics of data is called nonstationarity.

Nonstationary rainfall will result in nonstationary recharge. However, the relation between rainfall and recharge may also change with time. In Fig. 3 the lower panel shows three hypothetical recharge responses to the Gingin rainfall trend. The topmost line a stationary relationship between recharge and rainfall — here recharge is always 30% of the rainfall. With this stationary relationship, the 28% decline in the 25-year average rainfall from 1907–2022 also causes a 28% decline in recharge. The middle line illustrates a nonstationary relationship between recharge and rainfall. The less rainfall there is, the lower the percentage of the rainfall that forms recharge. Nonstationarity in the recharge arises both because the rainfall changes, and because the rainfall produces proportionally less recharge. In this case, the 28% decline in rainfall is amplified into a 90% decline in recharge. The bottom line shows recharge that is even more sensitive to declining rainfall, so that by 1990 recharge no longer forms. Empirically, this nonstationarity reveals itself in a changing ratio between recharge and precipitation. We report on this ratio, which we term the recharge fraction, throughout the study.

The sensitivity of the recharge to the rainfall volume is called the ‘elasticity’ of the recharge to rainfall. The elasticity of recharge can be examined with respect to climate as well as to landscape factors like the depth to water table, soil type, or land use. The elasticity of recharge to any one of these properties is likely to depend on the other properties. Mathematically, elasticity is the derivative of the recharge with respect to rainfall (or any other variable of interest).

Under a nonstationary climate, the stationarity and elasticity of the recharge and recharge fraction are important, because they indicate the risk that modest changes in climate could produce large changes in recharge. One way to explore nonstationarity in rainfall-recharge relations, and to identify which factors might affect recharge elasticity is to develop analytical models of recharge and the recharge fraction, which allow relationships and their derivatives to be computed directly.

4. Simple meta-analysis of recharge studies

To identify recharge studies relevant to the Gnangara groundwater system we searched the published literature using the Google Scholar and Scopus databases (last updated in September 2023). We used a search string of (“recharge” or “deep drainage” or “infiltration”) and (“Perth” or “Swan Coastal Plain”) and (“superficial” and “groundwater”). All returned manuscripts were reviewed, and those which provided original descriptions of groundwater recharge

measurement or modelling for the Perth Basin were retained. We also drew on two grey literature publications. The first, a “Review of Recharge and Water Use studies of Vegetation on Gnangara Groundwater Mound” by Silberstein (2010) is a technical report prepared for the Water Corporation of Western Australia. The second, “A Bibliography of Published Reports on Groundwater in Western Australia”, Smith et al. (1999) is a bibliographic database containing 1947 references about groundwater studies in Western Australia from 1912 to 1998, along with associated keywords and availability. From the database 74 studies associated with the keyword “recharge” and 24 with the keyword “drainage” were identified. Finally, we consulted several career hydrologists whose work focuses on the Swan Coastal Plain (Don McFarlane, David Schafer and Richard Silberstein) to identify additional data sources or reports we might have missed.

From this review, we identified 38 studies on the Swan Coastal Plain with 117 estimates of annual potential or net recharge. Of these, 34 studies and 97 recharge estimates focused on the Gnangara groundwater system. The studies spanned the period 1966 to 2017. We formed a database with an entry for each study reporting the year, the type of recharge estimated (e.g. potential or net), the methods used for estimation, the location of the estimate, land cover and other site data. Data were often ambiguous. For example, some studies did not specify the year in which recharge measurements were made (e.g. Allen, 1981; Davidson and Yu, 2008), while others presented estimates averaged over 2 decades (e.g. Xu et al., 2009). In these cases, we assigned the recharge estimates to the year of publication. Where a date range was provided, we assigned the estimates to the centre of that date range. Approximately a third of the studies presented recharge estimates as a range of values, which we represented with its arithmetic mean. Where studies did not report rainfall, we obtained rainfall information from local measurements in other studies that overlapped with the recharge estimates in space and time where possible, or by using rainfall observations made at Perth Aero Weather station (ID BOM: 9021). We

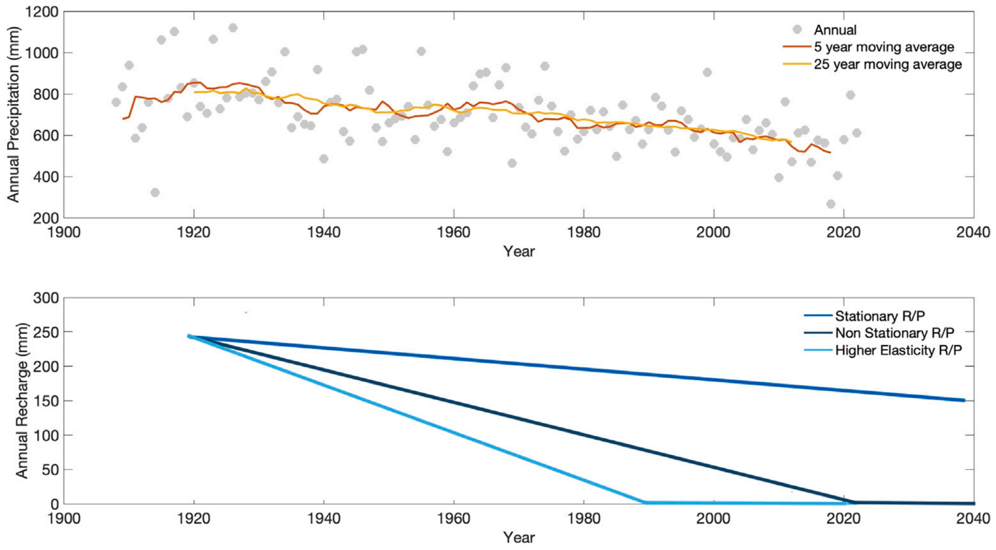

Fig. 3. Illustration of non-stationarity in rainfall at Gingin. The top panel illustrates large interannual variation in rainfall (grey points). Statistics of the rainfall — in this case the mean annual rainfall calculated on five and twenty-five year timescales, however, show clear trends. The dependence of the statistics on time means that the rainfall is nonstationary over the 1920–2020 period. The bottom panel illustrates three hypothetical (cartoon) responses of recharge to changing rainfall. In one case the ratio of recharge to precipitation is stationary, resulting in a similar trend in recharge to that in rainfall. In the next case, the ratio of recharge to precipitation declines as precipitation declines. This nonstationary relationship causes recharge to drop faster than rainfall does. In the final case, the sensitivity of the relationship – the elasticity – to rainfall is even greater, causing recharge to fall to zero. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

removed studies from the meta-analysis if (i) the recharge was unclear, (ii) data were repeated between studies, or (iii) the study could not be confidently associated with the Gnangara groundwater system. The final dataset was uploaded to Hydroshare and is available at the: http://www.hydroshare.org/resource/9df2a1a5bfb344b895976f68464e304c.

5. Analytical model for recharge over the Gnangara groundwater system

To explore how recharge and its elasticity might vary with climate and landscape factors, we formulated a simple event-based model of piston flow and evaporation from a soil column. The model's purpose was not to simulate dynamics at a site, but to explore the interdependence of soil, groundwater depth, and climate with recharge and its elasticities (Harman et al., 2011) .

The model imposes strong simplifying assumptions in order to enable the existence of an analytical solution. As explained in Section 6.1, which summarises understanding of the recharge process over the Gnangara Mound, these assumptions reflect the key features of the seasonality, soils and unsaturated flow in the study area. The assumptions are: (i) drainage of water within the soil after a rain event occurs instantaneously and redistributes all added water until the soil is uniformly at field capacity (s_f, where s_f is a volumetric water content) to a depth z_f [m] which defines the position of the wetting front (similar to Laio, 2006). (ii) Wetting fronts are sharp and follow a piston-flow process. (iii) There is an extinction depth z_{max}, such that wetting fronts passing below this depth are not depleted by wet-season evaporation, and (iv) At depths shallower than z_{max} [m], evaporation occurs at a fixed, equal rate at all soil depths, such that its sum satisfies evaporative demand PET [m/day]. Evaporation becomes zero when the soil moisture dries to the hygroscopic point, s_h.

With these definitions, potential recharge is generated by rainfall events that cause wetting fronts to cross z_{max}, i.e. when $z_f > z_{max}$. The depth of recharge for each of these events is given by $(z_f - z_{max}) \times (s_f - s_h)$. While this model can be explored for stochastic rainfall conditions, analytical solutions linking recharge to soil and climate properties can be derived for the simplified case of a mean storm depth of a [m] occurring at a fixed interval of λ days during a winter wet season (winter) of length T [days] during which PET is constant.

If the initial soil water profile is defined as $s(z)$ - that is soil moisture s is distributed across depths z according to the profile $s_1(z)$, then the depth of the wetting front caused by a storm with depth a is:

$$\int_0^{z_f} s_1(z)dz + a = (s_f - s_h)z_f \tag{1}$$

Following the rainfall event, the soil profile is updated from its pre-event condition to a post-event condition, s_2:

$$s_2(z, t = 0) = s_f, \qquad 0 < z \le z_f \tag{2}$$

$$= s_1(z), \qquad z_f < z \le z_{max} \tag{3}$$

That is, above z_f the soil is at field capacity, and below z_f the soil retains the original soil water profile for those depths.

Between events, the soil dries uniformly, provided $s > s_h$. The piston flow assumption implies that soil always wets from the top down. The hygroscopic point will first be reached at a depth $z_o(t)$, so that the rate of change of s is given by:

$$\frac{ds(z,t)}{dt} = -U(z,t), \qquad z \le z_o \tag{4}$$

$$= 0, \qquad z > z_o \tag{5}$$

where the rate of drying at each depth, U is determined by setting:

$$\int_0^{z_o} U(z,t) = PET. \tag{6}$$

At the end of a dry summer, the initial soil wetness can be assumed to be s_h at all depths. Once winter begins, the soil column will increase in wetness. For evenly spaced and equally sized storms there are two possible steady-state outcomes. One is that the evaporation that takes place between storms exceeds the water input per storm. In this case, the soil column does not wet up. Instead, the soil column will dry back to $s = s_h$ between each storm, and the same wetting front depth is produced for every storm, namely:

$$z_f = a/(s_f - s_h) \tag{7}$$

Alternatively, however, conditions may ultimately lead to the soil column wetting up completely, so that $s(z) = s_f$ for all z. This condition occurs if the time needed to evaporate the water added by each storm exceeds the time between storms, that is if $a/PET \ge \lambda$; here, the

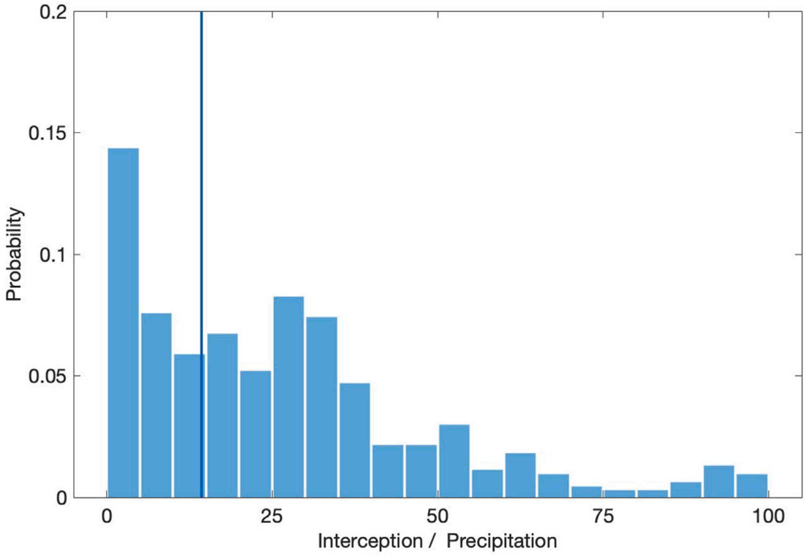

Fig. 4. Interception estimates from the Gingin site made under Banksia. This plot shows the distribution of interception as a percentage of rainfall across 590 measured events. Each point represents an average of the gauges that were reporting during each event. The vertical line shows the median interception loss of 14%. Note that these data are not adjusted for stemflow or with observations of concentrated throughfall fluxes at the site. As such, the data shown represent an upper limit on interception losses.

soil progressively wets and dries, and each successive wetting front increases in depth. The wetting front depth for the 'n'th storm is given by:

$$z_f(n) = \frac{na - (n-1)PET\lambda}{s_f - s_h} \tag{8}$$

If the soil was initially dry, it will take n^* storms before any recharge occurs — that is until $z_f > z_{max}$. To find n^* we solve:

$$n^* \geq \frac{(s_f - s_h)z_{max} + PET\lambda}{a - PET\lambda} \tag{9}$$

The total recharge depth for a winter of length T – representing potential recharge for the year – is given by:

$$R(T) = \left(\frac{T}{\lambda} - n^*\right)(a - PET\lambda) \tag{10}$$

Substituting in the expression for n^* and expanding, a simple analytical expression is obtained relating potential recharge to soil type, potential evaporation, average storm depth, average interval between storms and the length of the winter, T:

$$R(T) = \left(\frac{T}{\lambda} - \frac{(s_f - s_h)z_{max} + PET\lambda}{a - PET\lambda}\right)(a - PET\lambda) \tag{11}$$

$$R(T) = \left(\frac{Ta}{\lambda} - TPET - (s_f - s_h)z_{max} - PET\lambda\right) \tag{12}$$

Finally, the recharge fraction can be computed by dividing the computed recharge by the annual rainfall.

5.1. *Elasticity of recharge*

Eq. (12) allows the elasticity of recharge to be calculated by taking the derivative of R with respect to different climate parameters in the model. These elasticities are presented in Table 1. The elasticities can be interpreted such that a change in one quantity — for example, a 1 mm decrease in average storm depth a, would cause winter recharge to decline by $T/\lambda \times 1$ mm. We computed elasticities of winter recharge and explored the potential for changes in T, λ, a and winter PET to lead to non-stationarity in the recharge fraction.

Table 1
Elasticities of potential annual recharge with respect to changes in the duration of winter, the frequency of rainfall during winter, the average storm depth and the potential evaporation during winter.

Quantity changing	Elasticity
Winter duration (T)	$\frac{\partial R}{\partial T} = \frac{a - PET\lambda}{\lambda}$
Storm frequency (λ)	$\frac{\partial R}{\partial \lambda} = \frac{-Ta}{\lambda^2} - PET$
Storm depth (a)	$\frac{\partial R}{\partial a} = T/\lambda$
Potential Evaporation (PET)	$\frac{\partial R}{\partial PET} = -T - \lambda$

5.2. *Model parameterisation*

We parameterised the model with observations of seasonal soil moisture variations at the Gingin site, estimates of the shallow root zone depth for the understorey, and analysis of rainfall data for three time periods.

Daily rainfall and potential evaporation data were obtained for the Gingin townsite weather station (Australian Bureau of Meteorology station 009018) for the periods 1960–1970, 1990–2000 and 2010–2020. These data were firstly used to define the winter as the period of time when the average daily PET was less than the average daily rainfall rate. For these periods, we computed the average frequency and depth of daily rainfall events, and the average daily potential evaporation rate for these periods. We also computed the mean annual rainfall for the three different periods. These data are shown in Table 2.

The winter wet season length declined from approximately 4 months (May–August) in the 1960s, to 3.5 months (half-way through May–August) in the 1990s, to 3 months (June–August) in the 2010s. Potential evaporation was constant at 2.4 mm/day for each period. The shorter winter was associated with less frequent storms, dropping from 13 days of rain per month on average from 1960–1970, to 10 from 1990–2000 to 8 from 2010–2020. This corresponded to changes in λ from 2.3 to 2.9 to 3.75 days. The mean depth of the storms increased slightly over the same period. (Note that these statistics apply to the different winter durations). Annual rainfall decreased across the three periods. Soil parameters used were the hygroscopic point, set to 0.02 and the field capacity, set to 0.05 (see Fig. 6). The winter extinction depth was set to 1000 mm, similar to the rooting depth of annuals and shrubs in the region.

Table 2
Details of winter rainfall and winter potential evaporation rates measured at the Gingin Bureau of Meteorology Gauge over three distinct decadal periods used to drive the model. P refers to precipitationn in mm/month, RD to rain days in number of events per month, and PET to potential evaporation in mm/month. All data shown are the decadal averages.

Month	1960–1970			1990–2000			2010–2020		
	P	RD	PET	P	RD	PET	P	RD	PET
1	12	5	301	23	1	310	17	1	317
2	17	2	253	13	2	263	27	2	259
3	16	4	220	19	4	221	25	1	223
4	53	7	137	22	5	146	29	3	140
5	98	6	88	97	10	92	68	7	93
6	165	15	62	134	9	66	99	8	66
7	157	16	61	148	13	65	122	10	67
8	103	15	76	119	10	79	120	7	86
9	60	10	103	74	6	105	63	4	120
10	48	6	165	40	6	168	30	5	179
11	18	2	213	20	3	209	24	4	232
12	12	2	280	8	2	288	16	4	301
Winter defn.	May–Aug (120 d)			Mid May–Aug (105 d)			Jun–Aug (90 d)		
Winter P (mm)	523			450			341		
Winter PET (mm/d)	2.4			2.4			2.4		
Annual P (mm)	758			719			640		
Winter rain (d/mon)	13			10			8		
Av. winter storm (mm)	10			12			14		

6. Results

6.1. Synthesis of the recharge processes

6.1.1. Canopy and soil surface processes

Although most of the Gnangara mound is vegetated, rainfall interception measurements in the area are limited - a single study in *Banksia* woodland (Farrington et al., 1989a), and three in pine plantations found interception fractions ranging from 10%–25% of rainfall (Farrington and Bartle, 1991; Butcher, 1976; Silberstein et al., 2007). These rates are supported by measurements at the *Gingin TERN Ecosystem Processes* site, which suggest interception rates of 14% on average (see Fig. 4). Interception has not been measured in urban areas, on horticultural sites or pasture in the study region. While high rainfall interception might be expected from urban street trees (e.g. 29%–44% of rainfall for urban eucalyptus Livesley et al., 2014), average canopy cover in Perth's urban neighbourhoods is $8.9 \pm 4.8\%$ (Saunders et al., 2020), so such high interception rates apply to only a small area. The sensitivity of interception to a changing climate is poorly understood, but interception would be expected to increase as a fraction of rainfall for more frequent, smaller and lighter storms (e.g. Toba and Ohta, 2008; Rutter and Morton, 1977). The greater the interception losses, the less water that remains to contribute to recharge.

Sands in the study area are often hydrophobic (Roberts and Davidson, 1971), with complex hydrological implications. Hydrophobic soils produce preferential flow, leading to a non-uniform, concentrated wetting pattern, which often travels deeper into the soil than would uniform infiltration (Rye and Smettem, 2017a). Water repellency declines as soils become wetter (Rye and Smettem, 2018), with significant interannual variability (Rye and Smettem, 2015). There are some suggestions that non-uniform wetting on water repellent soils can enhance recharge (Stephens, 1994; Hendrickx and Walker, 2017) by promoting greater depths of wetting and sequestering water from evaporation. The importance of hydrophobicity for recharge fluxes in the study area remains unknown (Smettem et al., 2021).

Rates of bare soil evaporation are rarely measured in the study area. Under mature pine trees, Silberstein et al. (2007) reported bare soil evaporation rates between 49–54 mm/year, including evaporation from pine litter. Short-term experimental studies using Bassendean sands indicated that on uniform and wettable soils, Stage I (evaporation) rates from unsaturated soils were on the order of 1 mm/day (Rye and Smettem, 2017b) during a 5 day period when potential evaporation was on the order of 8 mm/day. Given the high permeability and rapid drainage in the sands, it may be the residence time of water in the surface soils (e.g. the soils from where fast evaporation can take place, Lehmann et al., 2019), which is most limiting bare soil evaporation.

6.1.2. Unsaturated zone processes

Recharge processes over the Gnangara groundwater system are defined by two factors: the energy-limited Mediterranean winter and the sandy, very well drained soil. Together, these conditions create an annual excess of water that moves rapidly into the soil, from where it is sequestered from evaporation and transpiration by all but the most deeply-rooted plants.

The two major soil landforms of the Gnangara Mound are the Bassendean dunes in the east and the Spearwood dunes in the west. Both consist of highly permeable sands. The formations are hydraulically similar (Salama et al., 2005a), and quite vertically homogeneous, although clay lenses, iron concretions and gravels occur. The saturated hydraulic conductivity (K_{sat}) of the sands is generally high and reasonably consistent across the formations — for example, across 22 measurements of K_{sat} on Spearwood sands, and 21 on Bassendean sands the minimum saturated hydraulic conductivity measured was 0.38 m/day for the Spearwood and 0.41 for the Bassendean sand; the maximum was 7.3 m/day on the Spearwood and 7.2m/day on the Bassendean, and the mean K_{sat} was 3.5 m/day on the Spearwood and 2.8 m/day on the Bassendean sands (Salama et al., 2005a). Salama et al. (2005a) found similar water retention curves for both soil types too. Fig. 5 shows water retention curves *developed by the authors* for Bassendean sands at the Gingin site. These curves show a pronounced nonlinearity in water content between −10 kPa and −100 kPa head, so that there is only $\approx 5-10\%$ difference in volumetric water content between dry sand and sand at field capacity (see Fig. 5). Combined with the high hydraulic conductivity of the sands, the low water storage capacity means that once hydrophobicity is lost, the profile wets readily, with a piston-flow-like response to rainfall. On shallow soils, recharge occurs rapidly in response to winter rains. On deep soils, winter rainfall is distributed throughout the deep soil profile. The piston-flow nature of the wetting up process is illustrated in the timeseries of soil moisture shown in the right hand side of Fig. 5 for the top 6 m of soil at Gingin, produced by authors' from data collected at the Gingin site.

Vapour fluxes (evaporation and transpiration) and the drying of the profile are related to vegetation type, season, soil/water table depth and the rooting depth of the vegetation. Over the deep-rooted banksia woodlands at Gingin, although potential evaporation rates vary by a factor of 4 (from $\approx$10 mm/day in January to $\approx$2.4 mm/day in June see

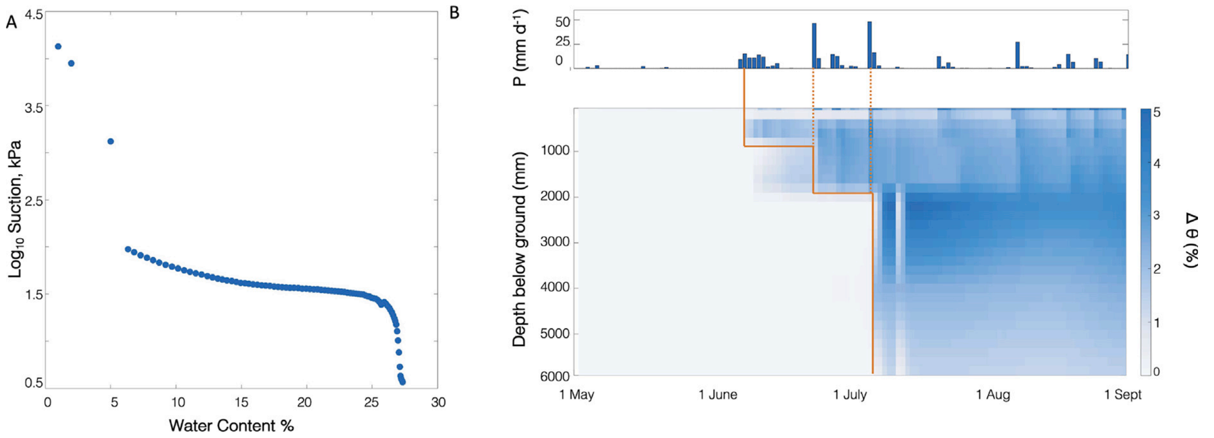

Fig. 5. (A) Water retention curve measured on Bassendean sand at the Gingin site. The soil is characterised by a strong nonlinearity in the water content — pressure relations, with very low water content (<5%) under approximately −1 m (−10 kPa/2 pF) of head. (B) Illustration of piston flow behaviour on Bassendean sands, based on soil moisture measurements taken at the Gingin site in 2019 (data interpolated between measured depths at 6, 10, 20, 40, 80, 160, 200, 400, and 600 cm). Data shown are the change in volumetric water content (%) relative to conditions at the start of winter. Orange lines indicate major events driving wetting and illustrate the piston-flow-like nature of the soil moisture dynamics.

Table 2), and rainfall varies by a factor of 6 (from ≤20 mm/month in January to ≥120 mm/month on average in July), actual evaporation measured at the flux tower varies by less than a factor of 2 (from approximately 40 mm/month in June to 70 mm/month in October). Estimates of recharge made from a vadose zone mass balance at the Gingin site (where recharge is computed based on monthly precipitation – monthly change in soil moisture storage – monthly evaporation), result in a long-term average recharge rate estimate of approximately 60 mm/year.

The annual variation in the vertical profile of soil moisture at Gingin is shown in Fig. 6. Minimal storage through summer (February and April) is replaced by sharp wetting fronts in early winter (June). By August the profile is full, with a 2%–3% increase in volumetric water content on average. After winter, the profile dries from above and drains from below, returning to minimum storage conditions.

The dimorphic root system of the *Banksias* and other native tree species allow hydraulic redistribution from groundwater or deep water stores to the shallow root system and soil, with unknown relevance for the regional water balance (Dawson and Pate, 1996; Burgess et al., 2000). In other ecosystems, hydraulic lift tends to increase water availability to vegetation, reducing recharge (Dawson, 1993).

6.1.3. Saturated zone

Water losses from the saturated zone are best studied in terms of groundwater use by native Banksia, which may depend on groundwater or use it opportunistically (Canham et al., 2009). Banksia species elongate their roots during summer to extract water from the capillary fringe, and the roots then die when water tables rise in winter (Canham, 2011; Canham et al., 2012). Groundwater uptake may represent up to 90% of Banksia water use in summer but may be as low as 5% with deeper water tables (Zencich et al., 2002; Zencich, 2003). Similarly, groundwater use of approximately 100 mm/yr by mature pines occurs when the water table is less than 15 m below the land surface (Silberstein et al., 2007). Thus, remote sensing analysis of the Gnangara groundwater system indicates approximately 100 mm/yr more evaporation over shallow (<6 m to water table) than deep groundwater (>6 m to water table) (Sommer et al., 2016).

6.2. Simple meta-analysis

6.2.1. History of recharge investigations in the study area

Hydrogeological studies exploring recharge to the Gnangara groundwater system were undertaken from the late 1960s onwards. Throughout the 1970s, three assessments of recharge over the Swan coastal plain (Bestow, 1971; Allen, 1976; Butcher, 1976), and the Gnangara Groundwater System (Bestow, 1976; Butcher, 1979) aimed to define

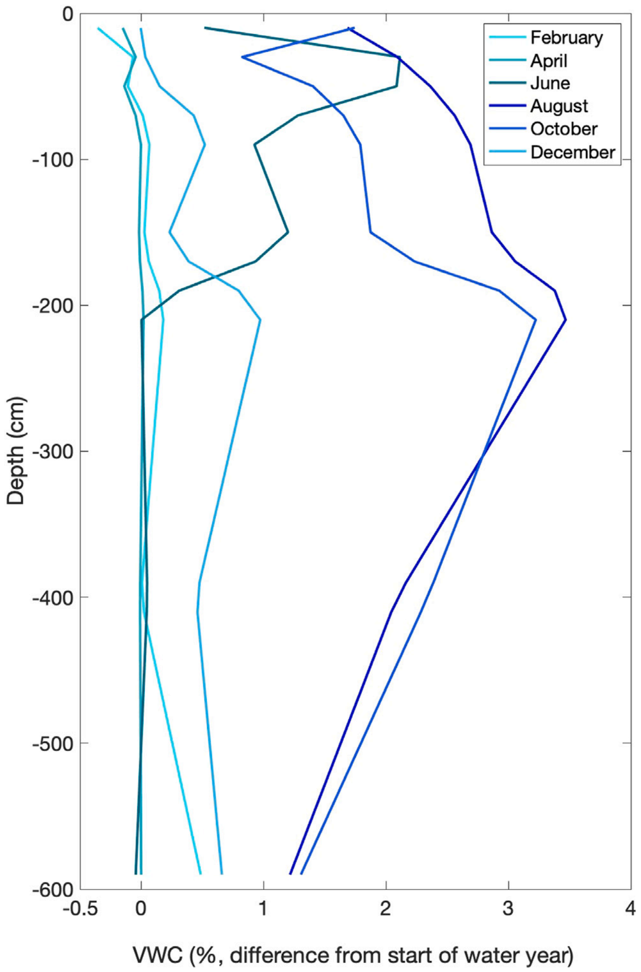

Fig. 6. Variation in soil water content over the top 600 cm of the soil profile at Gingin in 2019. Data are shown on two monthly intervals and are shown relative to the measured water content at the start of the water year (April). Note the very small range in water content on the horizontal axis, with only approximately 4 percentage points of variation in volumetric water content across the year.

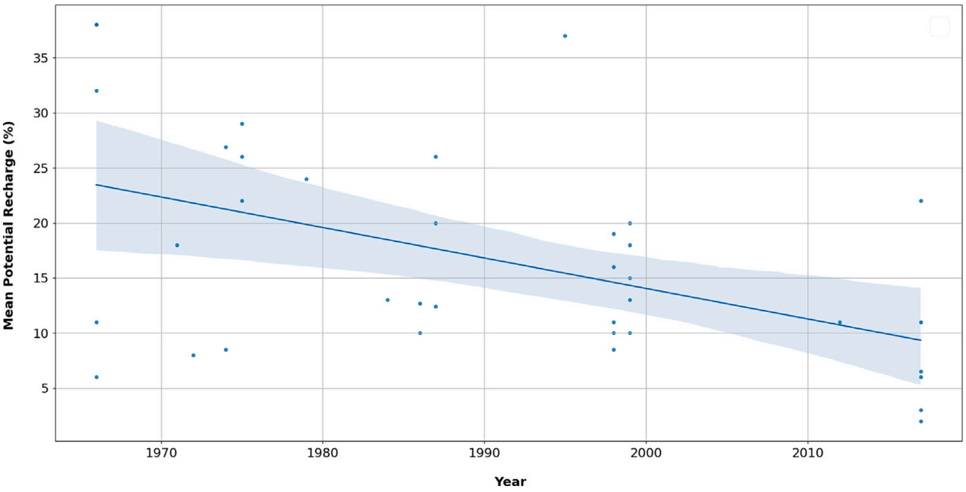

Fig. 7. Potential recharge as a fraction of annual precipitation, based on a synthesis of studies over the Gnangara mound area.

the regional water balance (Allen, 1976; Bestow, 1976) to inform urban planning and irrigation decisions (Bestow, 1971). These studies often compared recharge across land cover types, for example, Carbon et al. (1982) compared recharge under Banksia woodland, pine plantations and pasture on Spearwood sands.

Perth grew rapidly in the 1980s, creating an urgent need for water resources planning. Many recharge studies were undertaken in this period (Allen, 1981; McFarlane, 1981; Davidson, 1984; Carbon et al., 1982; Sharma et al., 1983; Sharma and Pionke, 1984; Sharma and Hughes, 1985; Perth Urban, 1987; Sharma et al., 1988; Thorpe, 1989; Farrington et al., 1989b; Sharma and Craig, 1989). The study methods include chloride mass balance (CMB) techniques as detailed by Gee et al. (2005), (i.e. Allen, 1981; Sharma et al., 1983; Farrington et al., 1989b; Sharma and Craig, 1989), water balance as explained by Nimmo et al. (2005) (i.e. Bestow, 1971; Sharma and Pionke, 1984; Farrington et al., 1989b; Farrington and Bartle, 1991; Salama et al., 2001), flownets as outlined by Richardson et al. (1992) (Allen, 1976; Carbon et al., 1982; Davidson, 1984), water table fluctuation as per (Crosbie et al., 2005) (i.e. Bestow, 1976; Farrington et al., 1989b; Salama et al., 2002, 2005b), environmental isotopes (e.g. ^{18}O, ^{2}H) or other tracers such as tritium or bromide as explained by Allison (1988) (i.e. Sharma and Hughes, 1985; Sharma et al., 1988; Thorpe, 1989). After this explosion of activity, relatively few recharge studies were conducted in the 1990s (Sharma et al., 1991; Farrington and Bartle, 1991; Davidson, 1995b; Appleyard, 1995), and most studies published in the 1990s describe earlier field measurements.

In the early 2000s, new robust numerical modelling frameworks for regional water resources were developed, and were supported by recharge estimation studies. Studies estimated recharge across different land uses and soils with the WAVES (Zhang and Dawes, 1998) unsaturated flow model (Davidson and Yu, 2008; Xu et al., 2008a, 2009), a simplified version of which was embedded as the main recharge estimation tool in the Perth Regional Aquifer Modelling System (PRAMS) framework (Barr et al., 2003; Xu et al., 2003a). PRAMS has now been critical to groundwater management and allocation in the region for 20 years. Despite growing awareness of the impacts of the drying regional climate on water resources and ecosystems, relatively few groundwater recharge studies took place from 2010-present, with the exception of some modelling work (Silberstein et al., 2013; McFarlane et al., 2019) supported by soil moisture profile observations.

6.2.2. Recharge estimates, trends and patterns

The diversity of recharge definitions, estimation methods, soils and land uses employed in the Gnangara area poses challenges for interpretation. By considering only studies over the Gnangara groundwater system we focus on the reasonably homogeneous Bassendean and Spearwood sands. We split the dataset into studies addressing net and gross recharge following the definition in Section 3.1. Fig. 7 shows potential recharge estimates, as a fraction of annual precipitation, by year. Individual recharge estimates from each study are presented as dots. The time trend for recharge across all studies is indicated by the line of best fit, with 95% confidence intervals around the line indicated with shading. The slope of the line is negative ($p < 0.05$), and indicates that across all studies – acknowledging the considerable variation in the dataset – recharge as a proportion of rainfall appears to have decreased from >20% before 1970, to close to 10% by the 2020s. Rainfall also declined during this period, and so that there was a greater than 50% decline in the absolute value of potential recharge.

For the net recharge estimates from the review, the trend of the recharge fraction is less pronounced than in the potential recharge, showing a reduction from approximately 22% to approximately 18% of rainfall. Absolute net recharge, however, declined by about 25%. Although the trends in Figs. 7 and 8 indicate a decrease in recharge either as an absolute value or as a function of precipitation over time, it is difficult to attribute the drivers of these changes due to inconsistent locations and methodologies across the studies.

A breakdown of recharge estimates (net and potential as a fraction of precipitation) by methodology and the vegetation cover of the site is shown in Fig. 9. Less recharge is estimated on sites associated with dense tree cover, such as pine plantations, and the highest estimated recharge values occur over pastures. CMB and numerical models were the most widely used methods, with 23 studies relying on CMB and 21 on numerical models. Fig. 9 shows that numerical models produced an ample range of recharge estimates and that this method was applied to every land cover type. Model estimates made on post-clearing land cover (i.e. pasture) produce some of the highest recharge estimates, but are not well corroborated empirically (save the single CMB estimate from Sharma et al., 1988). For a single method and land cover, large variations in the estimated recharge fraction occur. For example, modelled recharge under pasture varies from about 30% as estimated in the PRAMS model (Xu et al., 2008b) to values as high as 58% from a Richard's equation-based model (Sharma et al., 1988), and similarly high values estimated using the CMB method (Sharma et al., 1988).

The best-represented land cover in the dataset is Banksia, representing 42 of 97 or approximately 40% of the estimates. Recharge estimates under Banksia have been made using all the methods above. Considering the recharge variation over time in Banksia only may help to constrain variations due to land cover, providing a more readily interpretable dataset and which is comparable to the Gingin site.

Fig. 10 shows estimated recharge beneath Banksia over time, with blue and orange dots indicating potential and net recharge respectively.

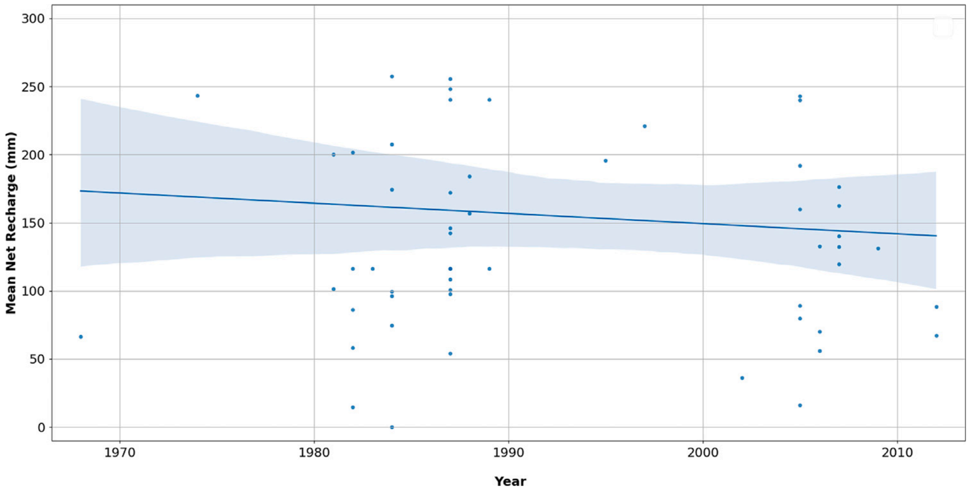

Fig. 8. Time series of net recharge estimates extracted from the review.

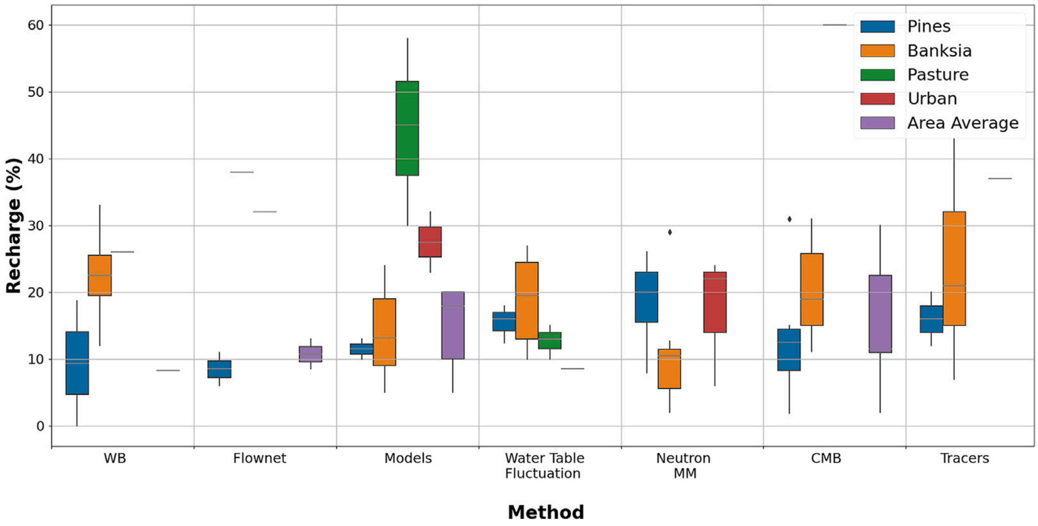

Fig. 9. Boxplots of the recharge estimates by method (columns) and land cover (colours). Here WB is water balance, WTF is water table fluctuation often assumed to represent potential recharge, Neutron MM is neutron moisture metre and CMB is chloride mass balance, often assumed to represent long-term net recharge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

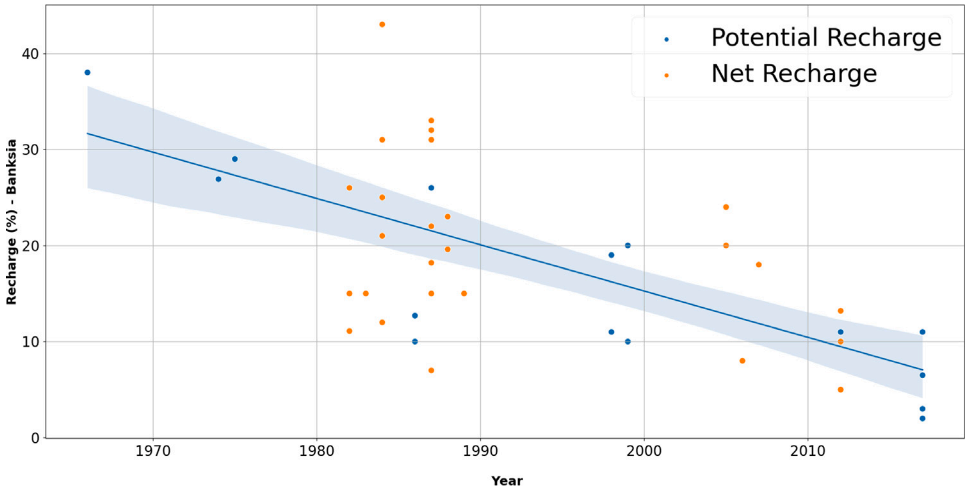

Fig. 10. Time series of potential (blue dots) and net (orange dots) recharge estimates under Banksia-classified land cover extracted from the review. The trendline applies to the entire dataset. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

It clearly indicates a declining trend in recharge. The linear regression fitted through these estimates that recharge as a fraction of rainfall fell from approximately 33% of rainfall in the 1970 period, to less than 10% of rainfall in measurements from 2000 onwards, a 65% reduction in the recharge fraction. The 20% reduction in rainfall over this period therefore resulted in an approximately 70% reduction in absolute recharge. McFarlane et al. (2019) estimated that recharge reductions would likely exceed rainfall reductions by a factor of 3: these data suggest a comparable, but larger factor of 3.5.

6.3. Modelled sensitivity of recharge at Gingin

Output from the analytical model is shown in Fig. 11. The top row shows annual potential recharge as a proportion of annual rainfall in colour, as soil and climate properties are varied. The properties of the Gingin site, and recharge estimates for the site are indicated with dots. Black dots correspond to the current climate, blue to 1990–2000 and red to 1960–1970. Only the black dot is seen on the soil plot, as we assume soil properties at Gingin have remained constant since the 1960s. All three dots appear on the other panels, illustrating the trend towards a shorter winter (smaller T), longer intervals between winter storms (larger λ), and more intense storms (larger a) in the Gingin area, as summarised in Table 2.

The top-left panel in Fig. 11 shows how recharge varies as field capacity (f_c) or the extinction depth for evaporation Z_{max} increase and shows a nonlinear relationship between potential recharge and these soil parameters. Recharge declines as extinction depth increases, as might occur, for example between sites with shallower or deeper-rooted winter-active vegetation. Recharge also declines as field capacity increases, reflecting the expected higher recharge on sands than on fine-textured soils. The central panel in Fig. 11 illustrates the sensitivity of potential recharge to storm properties. Recharge increases as the depth of the average storm (a) increases, and decreases as the time interval between storms λ increases. The panel on the right shows the sensitivity of annual potential recharge to the length of the winter T and to winter potential evaporation PET. Recharge declines as the winter gets shorter, and as potential evaporation during the winter increases.

The potential for non-stationarity in the recharge fraction R/P with changing climate properties is illustrated in the second row of Fig. 11 which shows how recharge fraction responds to rainfall climatology. Stationary conditions - a time-invariant constant recharge fraction as climatic properties changed overtime — would be indicated by horizontal lines in these plots. However, all plots indicate that recharge fraction would change with the changing climatic properties - i.e. that it would appear non-stationary over time. The simple model estimates approximately a 55% reduction in potential annual recharge at Gingin since the 1960s, substantially more than the 20% reduction in average annual rainfall shown in Fig. 3. This is comparable to, although lower than, the estimated 65% reduction in recharge fraction observed from the experimental studies over Banksia summarised in the meta-analysis. The model estimates that recharge fraction should be approximately 12%. This is similar to the 2010–2020 estimates for Banksia sites shown in Fig. 10 and produces a potential recharge estimate of 76 mm/year which is comparable to the estimates of 60 mm/year made by applying a vadose zone mass balance to the Gingin site (see Section 6.1.2).

Recharge elasticities shown in Table 1 indicate that the sensitivity of the recharge to changing climate is independent of landscape factors — that is, the sensitivity of recharge to a decline in the length of winter or storm frequency is independent of extinction depth or soil properties. The elasticities are linearly dependent on climate properties other than the average time between storms, λ, which is nonlinearly related to how sensitive recharge is to the length of the winter and to changes in λ itself. The smaller λ is, the more sensitive the recharge is to changes in λ: this is because large λ implies dry conditions that are relatively insensitive to rainfall frequency.

7. Discussion

7.1. Recharge processes and model response

Recharge is particularly sensitive to changes in climate during the winter wet season, including the length of the winter and the frequency and depth of rainfall events. Accounting for how these factors have changed at Gingin, the potential recharge fraction dropped from 26% of rainfall to 12% of rainfall. Considering that the annual rainfall also declined over this period, this reduction results in a decline in potential recharge of ≈117 mm/year — or a 60% drop in response to a 16% decline in annual rainfall, equivalent to recharge-rainfall elasticity of close to 4.

The decline in potential recharge relative to annual rainfall illustrated by the simple model at Gingin is lower than that identified in the empirical observations over Banksia. While much of this discrepancy can be attributed to the uncertainty in the empirical data, it may also indicate that processes omitted from the simple model are changing as the climate dries, amplifying reductions in recharge. For example, hydrophobicity could slow down early winter wetting of the soil, while increasing evaporative losses in early winter. Vegetation properties are not static, for example, the modelled extinction depth perhaps increased over time, if root systems are becoming deeper in response to the drying climate. Interception, which is omitted from the model, may well also be changing with changing storm properties and frequency change. The model also omits the effect of clustering large rainfall events during winter and potential changes in that clustering, which certainly influence recharge. At present, the sensitivity of these processes to climate remains unknown, as does their direct influence on recharge.

Even in the relatively uniform, ‘simple’ and well-studied recharge sites, process knowledge gaps remain. These gaps are principally around the transformation of rainfall to infiltration and the losses of water from the soil and groundwater as vapour; the impact of these processes on recharge, and their sensitivity to changing climate. Improved understanding of these processes and sensitivities will enable managers and research to anticipate and plan for non-stationarities in recharge.

Some of these uncertainties could be addressed through additional measurements at the *Gingin TERN Ecosystem Processes* site, for example by disaggregating evaporative fluxes into different water sources and processes — such as bare soil evaporation, plant water uptake from groundwater, or plant water use from the soil. At present, the only way to separate these processes is through calibrating models (Xu et al., 2008a, 2003b). Augmenting the site with sapflux observations, tracer experiments or isotopic analysis of water could assist in such disaggregation of the vapour fluxes, allowing these processes to be isolated and better understood. Current work at the site is seeking insights into interception processes and their sensitivity to rainfall and climate. Inverse modelling applied to independent observations might also provide a useful way to constrain estimates of loss processes (Lu et al., 2022).

7.2. Observed changes in recharge

Estimates of recharge fraction from the 1960s to present indicate a long-term declining trend. Potential recharge declined from approximately 25% of rainfall in the 1960s, to approximately 10% of rainfall by 2019; while the decline is somewhat lower when considering potential and net recharge together (24% in the 1960s to approximately 15% in 2019). The very low net recharge estimation in 1968 (Bestow, 1971) biases the linear regression towards low change and relied on strong assumptions in its methodology which may have underestimated regional recharge. Such an underestimate would reduce a declining trend that appears stronger amongst other forms of recharge.

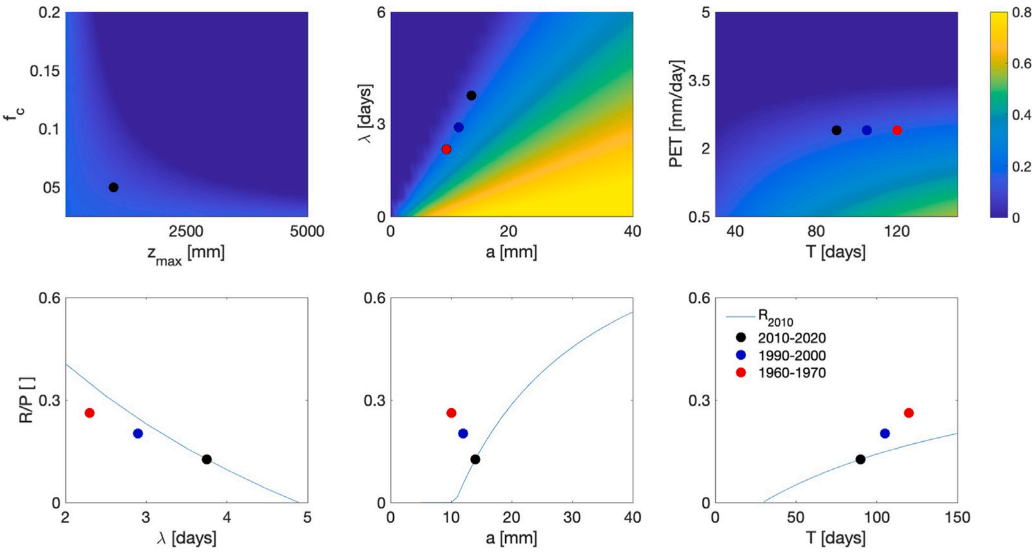

Fig. 11. Analytical model predictions of annual potential recharge fraction for conditions at the Gingin site. The top 3 plots hold all parameters constant at Gingin values other than the parameters varied on x and y axes. From left to right, these are field capacity (f_c) and extinction depth (z_{max}), mean interval between storms (λ) and mean storm depths (a), and potential evaporation (PET) and duration of winter (T). The conditions at Gingin during the 1960s are indicated with red dots, during the 1990s with blue, and 2010–2020 as black dots. The top left plot showing variation with soil conditions has only a single dot because we assume soil conditions did not change during the time period in question. Colours indicate the gross recharge as a fraction of annual precipitation. The bottom row shows the response of the potential recharge as a fraction of precipitation if rainfall characteristics and season length only are varied. These plots clearly show non-stationarity in the recharge fraction at Gingin (i.e. lines are not flat), and that this non-stationarity is emerging in the recharge fraction through multiple synchronous climatic changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The meta-analysis points towards the conclusion that as the climate dries, recharge represents a declining fraction of precipitation. This trend, however, remains confounded by the different methods and settings in which recharge was estimated. There is generally insufficient data to disentangle the effects of method, land cover/use, depth to groundwater and climate on estimated recharge fraction. Thus, the low estimates of recharge in the 2019 studies may reflect the climate, or the specific properties of recharge in an urban parkland and a specific geological formation (the Kings Park formation). Similarly, it is not obvious how to meaningfully compare estimates made via modelling with those made from chloride mass balance, soil column water balance methods or observations of borewell level fluctuations.

Long-term monitoring with standardised techniques would address many of these challenges, allowing trends at a site to be identified and differences between sites to be attributed to environmental, rather than methodological, differences. While the sophisticated observational infrastructure at Gingin OzFlux site is too expensive for very widespread deployment, monitoring networks could be built around heavily-instrumented locations like Gingin, using calibration of remote sensing tools, and intercomparisons of recharge estimates between different methods to constrain hard-to-measure quantities like ET at other sites. Emerging networks like the CZNET internationally, or the OzCZO network in Australia, provide logical hubs for long-term regional recharge monitoring.

7.3. Global relevance

The south-west of Western Australia lies at the southern edge of the dry subtropical zone, a zone that is expanding both north and south of the equator (Heffernan, 2016; Norris et al., 2016). This "expansion of the tropics", driven by climate change, cloud-driven feedbacks and natural climatic variability, places locations like the South-West of Western Australia that currently experience a benign Mediterranean climate at risk of rapid aridifaction (Lu et al., 2007). Thus, the trend of declining winter rainfall experienced over the Gnangara groundwater system is one that is likely to be repeated in groundwater systems in Mediterranean climates worldwide. A simple comparison of Koppen-Geiger Mediterranean climates, with a global assessment of areas that experience shallow groundwater shows that unconfined groundwater systems are prevalent in these regions. Many of these groundwater systems are important for human water use (e.g. Guermazi et al., 2019; Donoso et al., 2020), ecosystem health (e.g. Gamvroudis et al., 2017; Verones et al., 2012), and climatic moderation (Mu et al., 2022). Greater utilisation of groundwater resources is also being recommended as a mechanism to alleviate droughts in these regions (e.g. Olivier and Xu, 2019; Llamas et al., 2015). Sustainable management of many of these aquifers is already challenged: by over-abstraction (Acreman et al., 2022), drought (Thomas et al., 2017), and ongoing difficulties in making robust recharge estimates (e.g. Xu and Beekman, 2019).

The lessons learned from the Gnangara groundwater system suggest that water managers in Mediterranean climates should anticipate nonstationary relationships between recharge and rainfall in drying climates. If present, this non-stationarity relationship will amplify decreases in sustainable yield from these aquifers compared to what might be predicted from rainfall changes alone. Using detailed understanding of recharge processes to relate recharge to specific changes in winter storm climatologies is needed to quantify the specific nonlinearities and elasticities of recharge to local climate changes will likely be needed to inform locally-relevant management approaches. Conversely, management based on the assumption of a stationary recharge fraction under rainfall decline would, in general, be unwise and likely to over-estimate recharge.

8. Conclusion

A synthesis of recharge processes and meta-analysis of recharge studies conducted over the Gnagnara groundwater system on the Swan Coastal Plain, reveals that declines in rainfall in the area are amplified into declines in recharge that are 3–4 times greater. These responses are comparable to those predicted from a simple analytical model of the recharge process. Empirical detection of change in the area is possible, but contains uncertainty arising from the short duration, variable methodology and siting of most recharge studies in the area. Theoretical assessments of the sensitivity of recharge to climate change also contain uncertainty due to process knowledge gaps relating to how canopy interception, soil hydrophobicity, and soil moisture and groundwater use by deep rooted vegetation impact recharge, as well as the sensitivity of these processes to changing rainfall climates.

Despite these knowledge gaps and empirical limitations, the study clearly indicates that non-stationarity in recharge fraction should be expected in response to climatic drying in Mediterranean climates on well drained soils. Changes to climate that reduce recharge create nonlinear declines in the recharge fraction. This suggests a strong potential for recharge responses in Mediterranean basins to echo the nonlinearity in streamflow responses already seen in the South West of Western Australia — rather than declines in rainfall resulting in proportional declines in recharge, reductions in recharge are likely to be disproportionately large relative to annual rainfall changes. Scenario planning involving recharge as an input to groundwater resources allocation should consider the possibility of such reductions.

Better understanding the sensitivity of recharge to changing climate will require long-term monitoring (sufficient to detect changes in recharge and separate them from interannual variability), using consistent methodologies across sites, and elucidating the response of different components of the recharge process to climatic variables. Findings from these sites can be upscaled by benchmarking widespread observations such as those offered by remote sensing or borewell data to these monitoring sites, as well as by using observations for parameterisation and validation of modelling products. Such observations would be a valuable output from research networks like Critical Zone Observatories (Brantley et al., 2017), where equipment and long-term research support are available. If implemented across global observatory networks, these observations could help link process insights, and empirical recharge estimates with the growing understanding of the changing climate, leading to improved management responses against anticipated future recharge changes.

CRediT authorship contribution statement

Simone Gelsinari: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Sarah Bourke:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **James McCallum:** Investigation, Writing – review & editing. **Don McFarlane:** Data curation, Writing – review & editing. **Joel Hall:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Richard Silberstein:** Data curation, Investigation, Resources, Validation, Writing – review & editing. **Sally Thompson:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Simone Gelsinari reports financial support was provided by Western Australia Department of Water and Environmental Regulation.

Data availability

The link to the repository of the data for the metanalysis can be found at the link within the article.

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