Using models and high resolution monitoring to estimate recharge in south-west Western Australia

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Abstract: Robust recharge estimates are required to support groundwater allocation and ecosystem protection in the Perth Basin and adjacent agricultural zones of Western Australia. We applied a process-based, one-dimensional soil–plant–atmosphere model (WAVES) at five monitoring sites spanning a gradient of soils, vegetation, and groundwater depths. The monitoring sites include a comprehensive suite of instrumentation specifically developed assist in the estimation of recharge, including soil potential and soil moisture metres (at a variety of depths to the water table) and water table monitoring wells. One site was co-located at the Gingin Ozflux eddy-covariance tower, which provided estimations of actual evaporation. We extended the local observation data, with long-term climate forcing (1958–2023), and used measured soil hydraulic properties and site-specific vegetation parameters to simulate daily recharge over a 70 year period. Model performance was checked against available soil moisture and groundwater observations, and outputs were analysed to characterise inter-annual variability and controls on recharge. Results show marked differences among sites: mean recharge fractions ranged from ~5% to ~36% of annual rainfall, with the highest values at sites with minimal vegetation and coarse sands and the lowest at vegetated sites over deeper groundwater systems. The analysis confirms the utility of point-scale modelling for robust recharge estimation and parameterisation of regional models, while also highlighting uncertainties associated with actual evaporation, soil heterogeneity, vegetation phenology, and feedback with shallow groundwater. These models may be important tools for future water resource management, as they can capture non-linear responses in rainfall to recharge. This is particularly important for southern Australia where most global climate models are predicting further rainfall declines, however this study will have relevance nationally or internationally, where a robust understanding of recharge to unconfined, relatively shallow groundwater resources is required.

Keywords: *Recharge, WAVES, Recharge modelling, Infiltration*

1. INTRODUCTION

Groundwater underpins public water supply, industry, and groundwater-dependent ecosystems across south-western Western Australia (WA). Estimating recharge remains a central uncertainty in groundwater assessments because it depends on climate variability, soil properties, vegetation water use, and depth to groundwater, all of which vary strongly at local scales. Declining recharge rates over the past 20 years, in combination with groundwater use, has led to significantly declining groundwater levels in the Perth region. This has put stress on many important wetlands and groundwater dependent ecosystems. The recent Gnangara Groundwater Allocation Plan (DWER, 2022) recommends broad-scale cuts to groundwater allocations and public water supply entitlements to re-balance the water levels in the Gnangara groundwater area – but this comes at a significant economic and social cost. A better understanding of recharge and recharge processes is critical for robust management of this region, which has competing demands from water users and the environment whilst experiencing a drying climate. This study synthesises point-scale modelling at a highly instrumented site, and the expansion to five recharge monitoring sites representative of common land covers and soils in the northern Perth Basin: Dandaragan (pasture on duplex soils), Gingin (native vegetation on Bassendean sands), Gnangara (sparse pine mixed with native vegetation), and two sites at Whiteman Park (Banksia woodland and pasture). The objectives were to: (i) quantify long-term recharge and its variability; (ii) identify climatic and biophysical controls; and (iii) draw implications for parameterisation and prior constraints in regional groundwater models.

2. METHODS

2.1. Modelling framework—WAVES

WAVES is a one-dimensional, process-based ecohydrological model that solves coupled water and energy balances for layered soils with dynamic vegetation. A conceptual diagram of WAVES is shown in Figure 1. Soil water flow is represented using Richards' equation with hydraulic functions parameterised by soil texture;

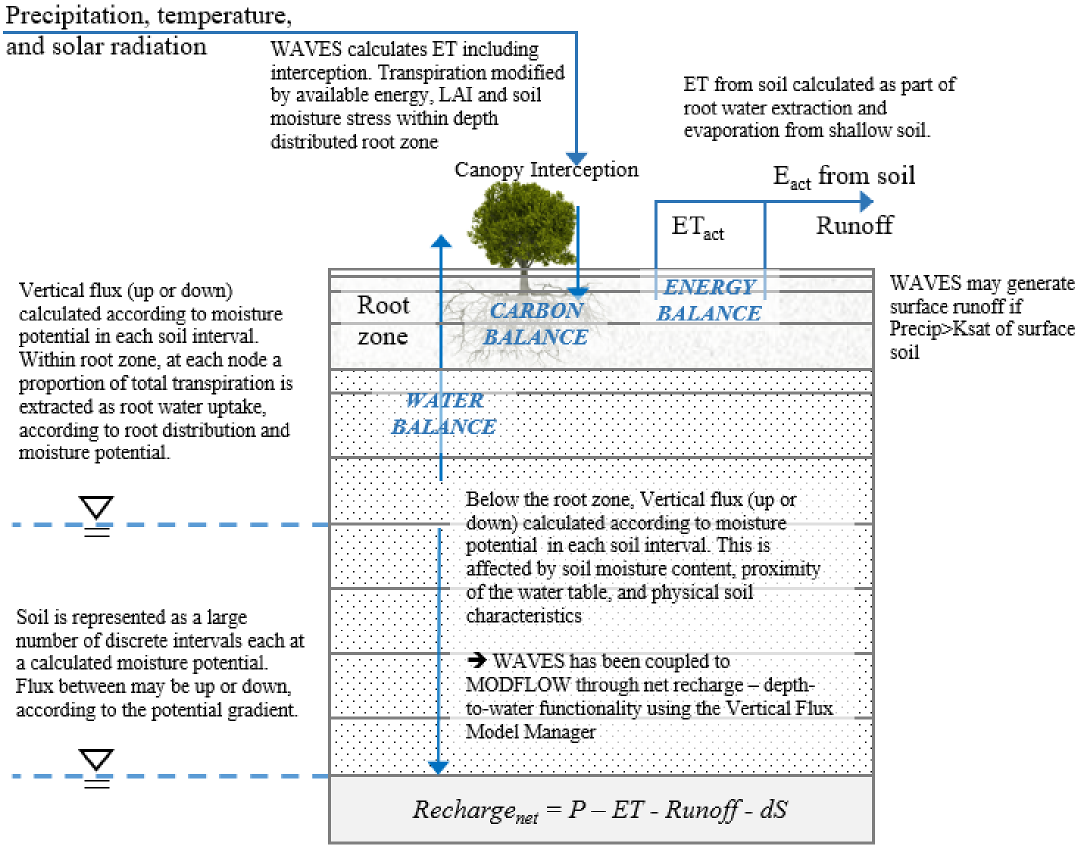

Figure 1 Conceptual diagram of WAVES

evapotranspiration partitions into soil evaporation and plant transpiration based on canopy state and meteorological forcing. WAVES is designed to simulate energy, water, carbon, and solute balances of a one-dimensional soil-canopy-atmosphere system (Dawes and Short 1993, Zhang et al 1996). It is a process-based model and integrates soil, canopy, and atmosphere with a consistent level of process detail. WAVES predicts the dynamic interactions and feedbacks between the processes. Thus, the model is well suited to investigations of hydrological and ecological responses to changes in land management and climatic variation. The soil water balance module in WAVES handles rainfall infiltration, overland flow, soil and plant water extraction, moisture redistribution, drainage (recharge), and water table interactions. Soil water movement in both the unsaturated and saturated zones is simulated using a fully-implicit finite-difference numerical solution of a mixed-form of Richards' equation (Richards 1931, Dawes and Short 1993, Short et al 1995). Overland flow can be generated when the rainfall rate exceeds the infiltration rate of the soil, and when rain falls on a saturated surface. Both of the mechanisms are considered explicitly in WAVES. A water table may develop anywhere within the soil profile. A regional groundwater depth may be specified, and changed on a daily basis with weather, that interacts with the WAVES soil column, however for this study the saturated water table was calculated explicitly by the WAVES model, and verified using local groundwater data. The carbon and solute balance components of WAVES were not used in this study.

2.2 Forcing data and parameterisation

As recharge to the water table cannot be observed directly, it has to be estimated via indirect methods that involve combinations of observed variables. Significant instrumentation to assist in the estimation of recharge was installed in 2021 by the University of Western Australia (UWA) as part of the Recharge Estimation Collaboration (Gelsinari, 2022). Instrumentation from UWA was installed at 5 sites across Perth's coastal plain, covering a variety of land cover and depth to groundwater. This instrumentation aimed to enable recharge estimation as a water balance residual within the unsaturated zone, as well as providing data that could be used for modelling assessment (input data, observation data and parameter data). The major effort in the monitoring campaign was to quantify soil water content and its variations in time and through space at each site using multiple complementary techniques: neutron moisture probes, frequency-domain reflectometers, and time-domain reflectometers. Soil water potential sensors were also installed at varying levels, and local weather stations were installed to collect high-resolution meteorological data. Water table bores were installed to collect local chemistry data and water table level information.

The Gingin site for the Recharge Estimation Collaboration was co-located at the Ozflux eddy-covariance tower, which was used for high resolution actual evaporation data observations. This tower was established in 2011 under the auspices of the Terrestrial Ecosystem Research Network (TERN). Instruments contained within the tower are akin to high precision high frequency meteorological units, measuring energy balance and exchanges of CO_2 and water between the land surface and the atmosphere. The instruments measure incoming and outgoing radiation, precipitation, humidity, temperature, soil heat flux, 3-dimensional wind velocity, CO_2 concentration and soil moisture content through the soil profile to the water table. The site also contains are several neutron moisture meter access tubes and an array of nested piezometers to facilitate groundwater profile samples dating back to 2011. These data have been collected continuously from inception to the present and, with few interruptions, provide a continuous record from which evaporation can be determined, and hence full water balance calculated.

The monitoring data was extended with long-term climate forcing data taken from SILO Data Drill locations that were modified to be consistent with local data (https://www.longpaddock.qld.gov.au/silo/gridded-data/). Leaf area index (LAI), used in the WAVES formulation, was taken from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (NASA 2024), however some smoothing and transforms of this data was required before this data was suitable as a model input.

Local soil samples were collected by the University of Western Australia to define soil parameters such as hydraulic conductivity, specific yield and soil water retention curves. Sonic drilling techniques were required for the installation of the soil moisture sensors, which allowed for the extraction of high quality cores for laboratory analysis. Physical properties of the soil samples were characterised through visual-tactile and soil particle distribution analysis (PSD) with a laser diffraction analyser. The soil water potential (SWP) and soil water content (SWC) were obtained using a pressure plate method, by applying eight negative pressures, i.e., 0.0 kPa (without pressure chamber), -5 kPa, -10 kPa, -30 kPa, -100kPa, -500 kPa, -1,000 kPa and -1500 kPa. Hardianti (2022) fitted the van Genuchten to the SWP and SWC data to develop the soil water retention curve (SWRC) for each soil sample. While van Genuchten fitting parameters were determined for each of the soil samples, the numerical formulation of the van Genuchten model has been shown to be unstable under a range of soil moisture and infiltration conditions, and hence these were re-fitted for the WAVES model using the, much more stable, Broadbridge and White (1988) methodology.

2.2. Calibration

Calibration of the WAVES model was applied deterministically against observations of actual ET at the flux tower (Figure 2), soil moisture storage (Figure 3) and water table dynamics (Figure 4). Along with the intensive soil moisture monitoring and locally precise climate data, long-term climate-forcing data was used to simulate

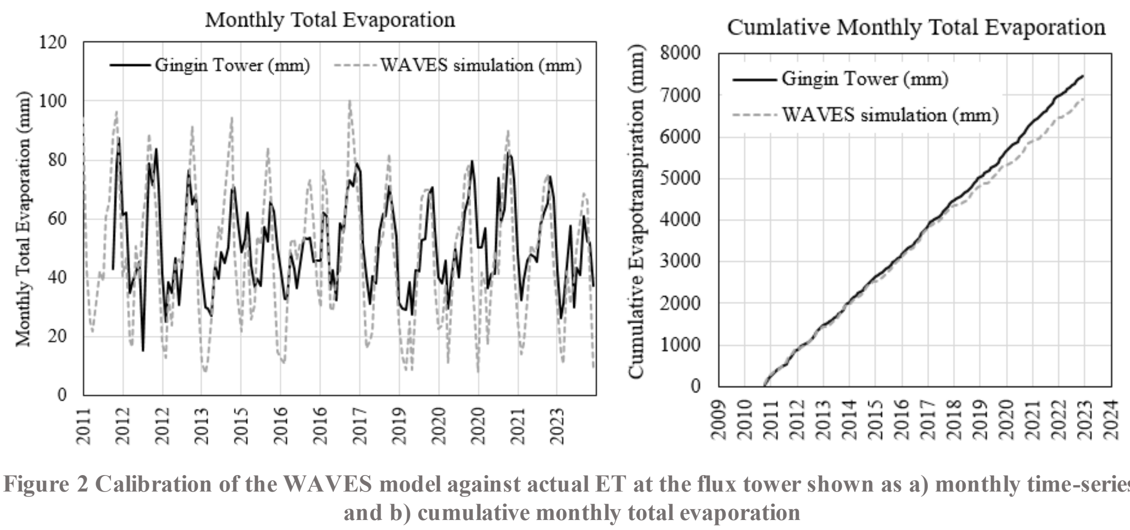

Figure 2 Calibration of the WAVES model against actual ET at the flux tower shown as a) monthly time-series, and b) cumulative monthly total evaporation

the model over a 66-year period (Figure 4). This simulation was run on a daily time-step with 79 computation nodes in the soil column to 12.5 m. The model was set up with a draining bottom boundary, to allow representation of recharge drainage (or horizontal flow of the regional groundwater system). In order to represent the influence of groundwater movement we set a bottom boundary hydraulic conductivity moderator, which throttles back the saturated conductivity in the bottom node. The simulation replicates the water table, and its decline over the last 50 years. The impact of the wetter period in the 1960s is clearly evident with simulated rise in water table, as is the impact of the recent wet year in 2021

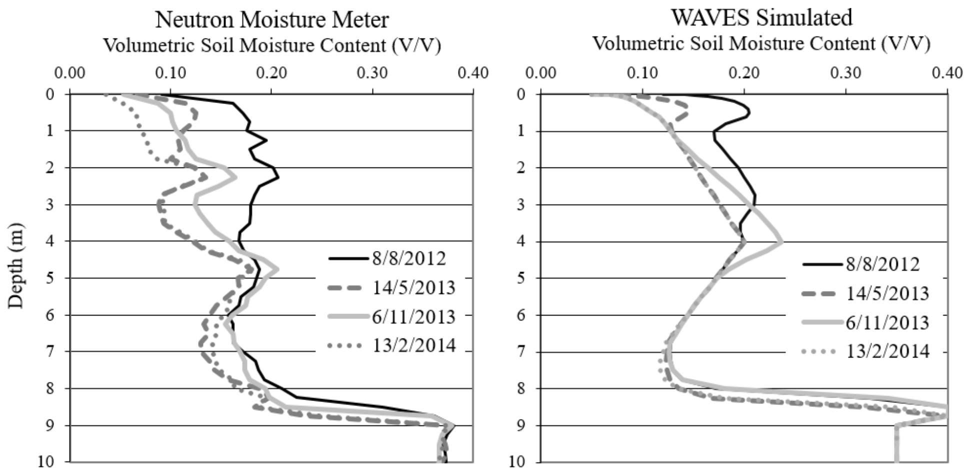

Figure 3 (a) Observed soil moisture profiles at Gingin for soil layer estimation (Data from early neutron moisture meter measurements). (b) Simulated moisture profiles on the same dates as observations.

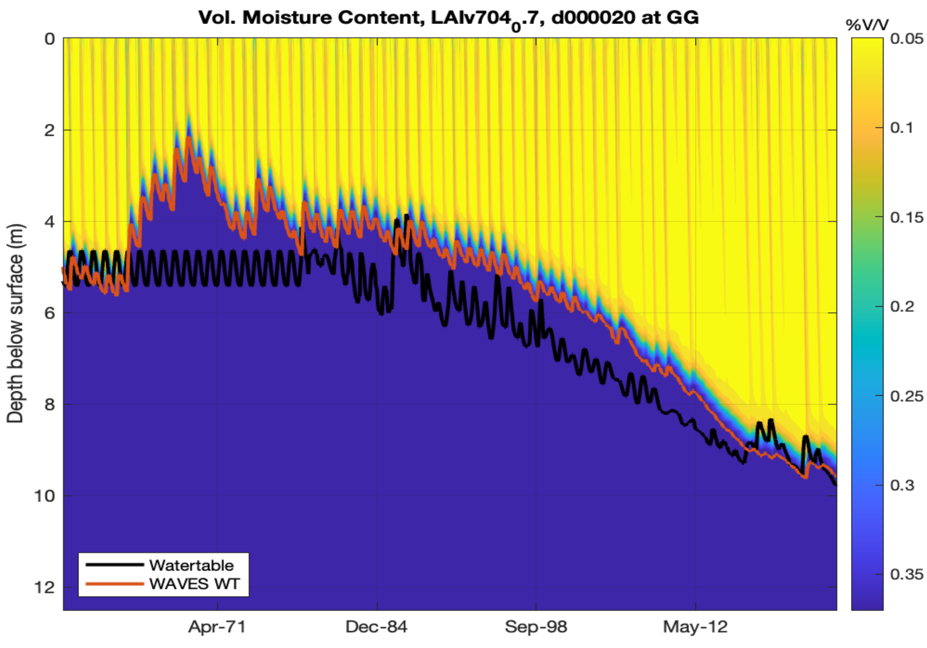

Figure 4 Volumetric water content and water table as simulated by WAVES in long-term simulation. The measured water table in a nearby bore is shown in black. The seasonal regularity in the measured water-table at the beginning of the simulation comes from the hindcasting of water table based on the monthly mean values in the first ten years of record. The vertical orange "stripes" indicate the seasonal periods of water infiltration.

3. RESULTS

Continuous daily simulations were preformed from 1958 to 2023. Annual values of recharge are plotted in Figure 5a, demonstrating the significant reductions in recharge over this 60 year period, particularly between 1980 to present day, which is largely responsible for the falling water table levels over the past 40 years. The period 1960-1990 estimated an average of 82mm recharge, whereas the period 1991-2024 estimated 21mm, a reduction of 74%. Relationships between annual rainfall and annual recharge were evaluated using a scatter plot (Figure 5b). The scatterplot shows that approximately 650mm of annual rainfall is required to generate recharge, and negative recharge will occur in particularly dry years.

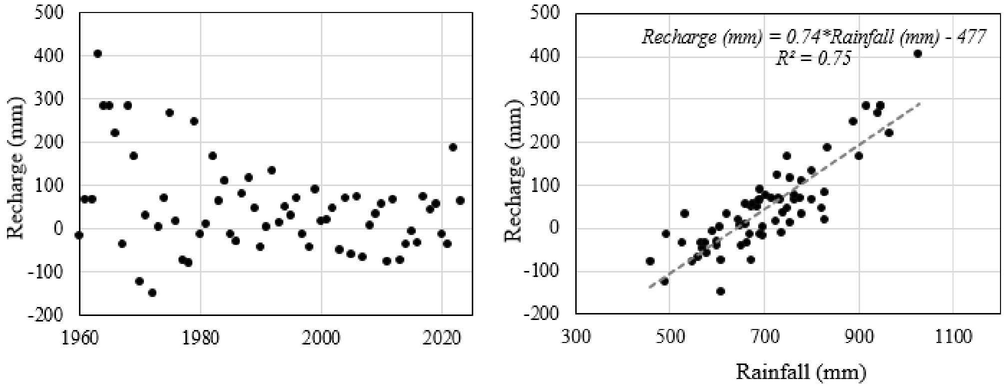

Figure 5 a) time-series of simulated annual net recharge and b) scatterplot of annual rainfall vs net recharge rainfall vs recharge for Gingin site, for the period 1960-2023

4. APPLICATION TO OTHER LOCATIONS

WAVES uses a parameter to describe the LAI to control ET rates (in combination with climate inputs, available soil-water, and root depth and distribution). Various methods for developing LAI values were tested using the Gingin site, where ET was measured. A transformed version of MODIS LAI was eventually adopted which resulted in a good match between actual ET and WAVES modelled ET. This method for collecting and transforming LAI information was used for all sites in a similar manner. Thus the remaining 4 sites were calibrated to water table and soil moisture observations only, using their site-specific observation data, climate data and soil parameter data. The range in net annual recharge for each of the locations is shown in Table 1, and scatterplots showing annual rainfall vs annual net recharge is shown in Figure 6.

Table 1: Modelled decadal water balance at Gingin under Banksia woodland

Site	Land cover	Soil	Depth to groundwater	Net annual recharge (% of rainfall)*
Gingin	Banksia - medium density	Med-coarse sands	Moderate (4m)	5% (-11% - 23%)
Whiteman Park #1	Banksia - medium density	Med-coarse sands	Shallow (2-3m)	22% (6% - 33%)
Whiteman Park #2	Pasture	Med-coarse sands	Shallow (2-3m)	36% (29% - 45%)
Gnangara	Mixed low density pines	Med-coarse sands	Deep (10m)	29% (14% - 40%)
Dandaragan	Pasture	Silty sand	Deep (8m)	15% (6% - 29%)

* values represent median with 10th and 90th percentiles in brackets, for the period 1960-2023

5. DISCUSSION

The paired Whiteman Park sites demonstrate higher recharge under pasture than under Banksia woodland on similar soils, consistent with higher LAI and year-round transpiration in the woodland. Deep, coarse sands at Gingin exhibit much lower recharge rates in later years, higher transpiration rates with deeper plant-root profiles, and more infiltration required each year for drainage to reach the water table. At Dandaragan, lower rainfall and duplex profiles reduce percolation and increases soil storage and negative soil potential, yielding lower recharge fractions. The pasture site at Whiteman Park has far more recharge at low rainfall rates (500-700mm), compared to woodland sites, indicating that these regions (as well as urbanised regions) will be more responsible for overall recharge to the Gnangara groundwater resource if future climate continues to become hotter and drier in south-west WA.

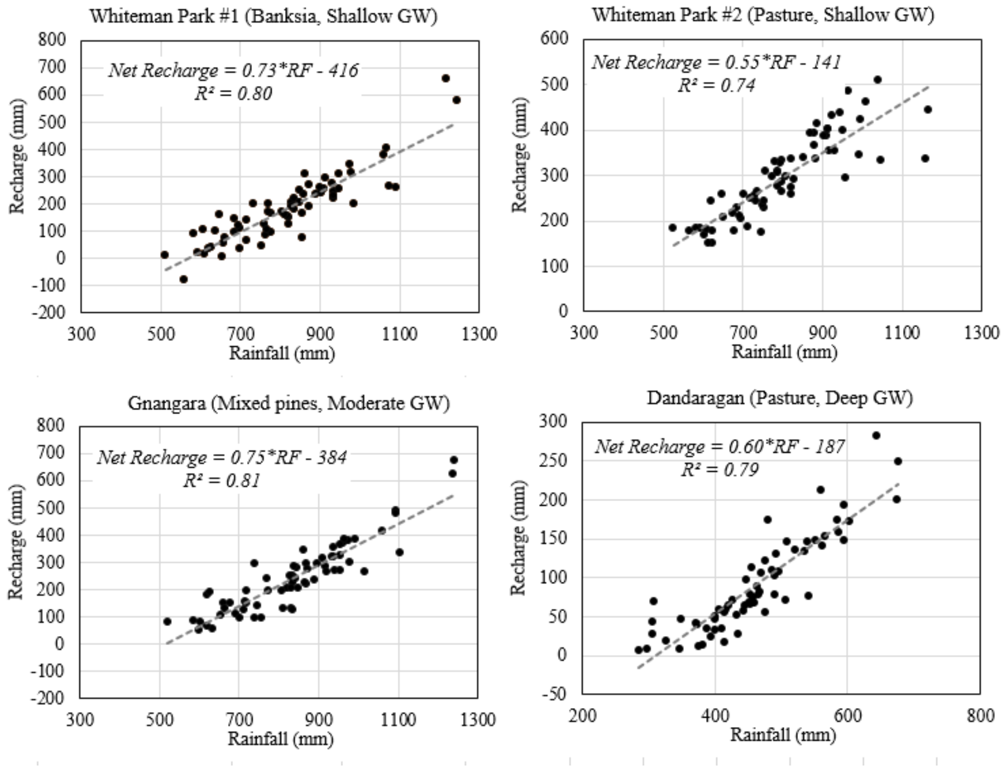

Figure 6 Scatterplot of rainfall vs recharge for the period 1960-2023 at the remaining four measurement sites

Recharge is concentrated in winter months when rainfall exceeds evaporative demand. Inter annual variability in recharge is strongly related to annual rainfall, however non-linear responses can be evident where soil storage limits or groundwater feedbacks become important (identified in Gelsinari, 2024). The strong rainfall–recharge relationship supports the use of climate index scaling, – useful for conceptually understanding recharge rates in the Gnangara groundwater region. However, uncertainty in these estimations should be considered, as rainfall timing, depth-to-groundwater, antecedent soil moisture conditions and land cover changes can all impact this relationship.

The site-specific soil and vegetation parameters provide prior information for complex regional recharge models. Having estimations of recharge at various points within a regional model domain can also be used to constrain flows in groundwater models, and would be an ideal application for the Perth Regional Aquifer Management System model (PRAMS, Saide et al, 2024). Further work to modify WAVES models to develop emulators for recharge to apply to regional models would be a worthwhile exercise, by simulating a large combination of land cover, climate, depth-to-groundwater and soil. Alternatively, the rainfall-recharge relationship for various land cover types could be used as an empirical recharge function for groundwater models, incorporating the scatter in the plots as prior data for history matching.

Significant uncertainty remains in the recharge estimates, and more data, or further analysis could be used in future studies to either quantify or to reduce the uncertainty in these estimates. To better calibrate the models, and/or to quantify uncertainty, mathematical methods could be employed, rather than using manual fitting. In particular, the method would benefit from using data assimilation software (Doherty 2015; White 2018) to automate history matching processes using various observation datasets. Soil-potential data was collected as part of the field program, however due to the installation of the instruments and disturbance of the soils, the data for their first year was not able to be used in the analysis. Future analysis could also include this data.

For sites outside of Gingin the largest source of uncertainty in recharge estimates was related to the actual evapotranspiration rate. WAVES used leaf area index based on MODIS data. There are however, concerns as to the suitability of the MODIS LAI data sequences for this environment. In addition to ground-truthing of LAI, better estimations of evapotranspiration using remotely sensed data would greatly benefit these estimates, particularly if these were scaled to local actual evapotranspiration measurements, or incorporated with data assimilation. Flux towers have traditionally been the only method available to measure actual evaporation rates at a small timescale, however more cost-effective and readily transportable instruments are now available, and could be used to provide another dataset to assist in these calculations.

Finally, these estimates of recharge would benefit from being tested against other methods – to compare and contrast methods, and to analyse where there are outlying values in individual methods. Other methods could include using other models to estimate recharge, for example HYDRUS (Šimůnek et al 1999), water balance methods, or tracer/isotope methods.

6. CONCLUSIONS

The high quality observation data available for this project provided a significant dataset from which a robust estimation of daily recharge was calculated using the WAVES model. WAVES simulations at five representative sites in south-western WA indicate substantial, systematic variation in recharge controlled by soils, vegetation, and climate. Mean recharge fractions span ~5–36% of annual rainfall, with highest values on shallow, coarse sands and lowest under deep wooded sites Banksia on sites with stronger plant water use. The findings from this project not only provide valuable insights into historical recharge trends but also lay the groundwork for future modelling efforts that account for climate variability. As water resource managers face the complexities of changing precipitation patterns and their impacts on groundwater, our robust recharge estimations will enhance the accuracy and reliability of numerical groundwater models. This research contributes to better-informed decision-making and the sustainable management of water resources, ensuring that groundwater models can effectively support the development of adaptation strategies in the face of climate change.

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