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Optimising the management of plantation, water and environmental assets

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Mount Gambier Centre

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Optimising the management of plantation, water and environmental assets

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Mount Gambier

by

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Executive Summary

South Australia is the first jurisdiction in Australia to licence plantation forest for water use via the *Water Allocation Plan for the Lower Limestone Coast Prescribed Wells Area*. This requires the forest industry in the Lower Limestone Coast (LLC) to develop and use a set of bespoke tools to optimise the management of its plantation, water and environmental assets. This report summarises the outcomes of a National Institute for Forest Products Innovation (NIFPI) project titled *Optimising the management of plantation water and environmental assets* (Project NS024). Research has been undertaken with the broad aim of improving the understanding and measurement of plantation water use and environmental asset management with four main objectives:

- Remote sensing - to derive near-daily estimates of tree water use at 10 m spatial resolution, and deliver estimates through a cloud-based tool that may present an alternative to the current forest water use accounting tool
- Ground monitoring - conduct plantation water use monitoring with installation of equipment at plantation sites to:
    a. add to existing water use monitoring data collected between 2000 to 2009, and
    b. ground truth (calibrate) the remote sensing tool output to measured data
- Wetlands - examine wetland setbacks, their derivation, impact and improved means of managing wetlands for plantation managers
- Groundwater recharge - Improve the estimated recharge across the LLC water allocation plan area and examine the uncertainty of the estimated recharge values

Outcomes from each component of the research are summarised below.

Remote sensing

The remote sensing component of this project has delivered the Forest EvapoTranspiration at High Resolution (FORETHIR) tool which uses satellite derived information to estimate evapotranspiration and by association, an estimate of the site water balance across the plantations of the LLC. The tool was calibrated using available data from eight forest sites in the LLC, and may be used to assess variations in water use across the landscape. The tool may be readily applied globally, but is only calibrated to LLC plantations. FORETHIR provides daily forest water use products at a resolution of 10 m × 10 m, making it higher spatial and temporal resolution than other products available to the industry. It currently has an accuracy of *0.4-1.8 mm/day RMSE* making it on par with the national product CMRSET, but greatly improves upon other models in its spatial and temporal resolutions. Based on the findings and discussion contained in this report it was recommended that:

- Field monitoring should be expanded further to capture greater variety of plantation environments, namely more sites in softwood, and over depths to water between 6 to 15 m for the purposes of calibration and validation of the forest water use model.
- Investment in the application of FORETHIR ET and extraction/recharge products for forest health and stress monitoring, groundwater-forest interactions, and bushfire risk and severity forecasting.
- Opening up the potential access to the tool by porting the tool into an open-source software environment (e.g. Python).

Ground monitoring

The ground monitoring component of this research has added eight forest water use field monitoring sites to the available dataset on plantation evapotranspiration in the LLC region. It has been used for both remote sensing calibration and to support improvement to existing approaches for empirical estimates of plantation water use. There were a number of recommendations made based on the monitoring:

- More research is warranted into the water use behaviour of trees immediately after thinning operations to verify how characteristic the relatively high water use at the monitored pine site was, as this project monitored immediately after thinning
- The data suggests that groundwater extracted occurred at both pine sites where depth to groundwater was estimated to be 6.5 m, a level slightly above the currently assumed extraction threshold of 6 m in the LLC water allocation plan – however, extraction was also at a rate much lower than the currently applied extraction rate in the LLC water allocation plan. It is recommended that water use monitoring should continue to occur, particularly where the water table is at 6 to 9 m, to further explore water use characteristics in this zone.
- Blue gum sites were using less water than currently assumed by the LLC water allocation plan. This may be because of the age of the monitored plantations (approximately 16 years) or site characteristics. It is important that more eucalypt sites with an age of less than 11 years are monitored to ensure that the currently assumed peak extraction rate (3.64 ML/ha/year) is not over estimated.

Groundwater

The groundwater recharge research has examined four approaches to groundwater recharge estimation and demonstrates the importance of using long term data to estimate groundwater recharge and ultimately assess available water for plantations and other water demands. For gross and net recharge estimation, there are several ways that the employed methods could be improved:

- for spatial analyses, utilise dynamic spatial data sets rather than static land use and water course / water feature data sets. This should leverage the Digital Earth Australia Land Use and Water Observations from Space. This would allow better assessment of land use types for temporal mapping exercises as well as inform individual groundwater well assessments.
- For future projections, utilise the BOM Australian Water Outlook to gain an ensemble of rainfall and potential evapotranspiration.
- For the specific yield uncertainty, we recommended applying the approach presented in Crosbie et al. (2019) to better capture the point uncertainty rather than the geostatistical approach used within this study.

In terms of the use and production of groundwater depth maps, there was variability over the period from 2004 to 2022. It was recommended to avoid the use of groundwater level snapshots from a particular year across the LLC region as representative. It would be more robust to use averages of longer time periods (5, 10 or 20 years) unless specifically reporting on the state of the resource at a particular time. The selected baseline has a large impact on the volume of water use being estimated in the LLC water allocation plan, which may tip the scales in terms of allocation status across management areas.

It was also recommended the adopted recharge values determined using the water table fluctuation method be updated. To allay some of the concerns raised in the water table fluctuation method from sparse sampling, recharge estimation could be improved with increased use of groundwater level data loggers in observation wells.

Finally, it was recommended that aggregate scale water use (licenced extraction) data for unconfined management zones of the LLC water allocation plan are publicly available as this will allow for independent and full accounting of the water balance across the LLC. At present, independently assessing water use is not possible.

Wetlands

The wetlands review activity has revealed several knowledge gaps and challenges related to wetland management in the LLC. The review made the following key recommendations:

- there should be a specific definition of groundwater dependent ecosystems provided in local policy documents. Methods used to determine what is, and is not, a groundwater dependent ecosystem should be considered.
- There appears to be little ‘on ground’ assessment of the status of LLC wetlands as groundwater dependent, or not groundwater dependent, available in the public realm which can be used to verify the findings of the current broadscale assessment methods from desktop assessments. Where such data exists for individual wetlands by land managers, it should be made available to other stakeholders for further verification.
- Ultimately, some consideration of the 14,373 features listed in the LLC prescribed wells area is considered necessary to determine which of the wetland features in the LLC region currently exist and need management, which do not exist and may be restored, and which have never or currently do not exist in any meaningful way.
- Due to the limited resources for assessing and prioritising efforts to manage and restore wetlands (by authorities or other organisations), it is recommended that one technique suitable for condition and value assessment be selected and commonly applied in the LLC region.
- Forest management guidelines should provide more explicit guidance about what should occur in a setback area – for example, advice on how a setback should be vegetated (if at all), and what management practices should be in place to prevent weed growth.
- Authorities and industry should consider research comparing the impacts of different setback management techniques on wetland condition over time. Existing studies that have informed guidelines are not clearly defined or available.
- Forest managers should ensure that up to date records of high and very high value wetland locations are maintained and seek information from authorities about what features may soon be acquiring high or very high value status. Authorities should likewise seek to inform landowners of the existence of high and very high value wetland and other groundwater dependent ecosystem features on their land when identified.

Uptake of recommendations

All research outputs were developed to inform key knowledge gaps related to the refinement of the current water allocation plan in the LLC pertaining to plantation forest water use and are intended to contribute to the science underpinning the plan. Immediate means of uptake include ensuring that findings are part of the currently active review of the LLC water allocation plan led by the South Australian Limestone Coast Landscapes Board.

Table of Contents

List of Acronyms

DEW	South Australian Department for Environment and Water
DTGW	Depth to groundwater
EG	*Eucalyptus globulus*
ET	Evapotranspiration
EVI	Enhanced vegetation index
FORETHIR	A Tool For FORest Evaporation at High Resolution
GDE	Groundwater dependent ecosystems
GVMI	Global vegetation moisture index
LCLB	Limestone Coast Landscape Board
LLC	Lower Limestone Coast
LLCWAP	Water Allocation Plan for the Lower Limestone Coast Prescribed Wells Area (Government of South Australia, 2019) (often referred to as the Lower Limestone Coast Water Allocation Plan)
PR	*Pinus radiata*
NIFPI	National Institute for Forest Products Innovation
Obswell	Groundwater observation well (typically those operated by DEW)

1 Introduction

South Australia is the first jurisdiction in Australia to licence plantation forest for water use. Plantation water use is licenced in the South East of South Australia based on the requirements of the *Water Allocation Plan for the Lower Limestone Coast Prescribed Wells Area* (often referred to as the Lower Limestone Coast Water Allocation Plan, LLCWAP) (Government of South Australia, 2019), which is developed to ensure the sustainability of groundwater resources in the region. This situation requires the forest industry in South Australia to develop and use a set of bespoke tools to optimise the management of its plantation, water and environmental assets. Currently plantation water use is estimated by deemed rates which have been developed based on a model of plantation water use (Harvey, 2009). Short of clear-felling plantations the industry has few options for adaptive management of water.

Organisations that operate industrial sites or irrigation assets are equipped with water meters where actual groundwater use is measured and known. Licenced water users in the region innovate constantly to ensure the optimum use of the available water licences for their chosen crops and other productive uses, and maximise the flexibility in their management practices. Because of this, the forest industry also requires innovative solutions to ensure they can compete for land, water and human resources in the region.

This research has been undertaken as part of a National Institute for Forest Products Innovation (NIFPI) project titled *Optimising the management of plantation water and environmental assets* (Project NS024). Research has been undertaken with the broad aim of improving the understanding and measurement of plantation water use in the Lower Limestone Coast (LLC) of South Australia, with the objectives outlined in the following section.

1.1 Study objectives

There were four main components of research in the project related to remote sensing, ground monitoring, wetland setbacks and groundwater recharge. These are detailed further below.

1.1.1 Field monitoring of plantation water use

Key aims of the ground monitoring works in this project were to:

- review options for plantation water use estimation to identify the best approach available
- review previous investigations into plantation water use and undertake individual tree ET measurement
- conduct plantation water use estimation with installation of equipment at four plantation sites examining different species, different soil conditions and varying depths to groundwater. Collection of data will be undertaken to:
    a. add to existing plantation water use monitoring data collected from 2000 to 2009 by CSIRO, and
    b. ground truth (calibrate) the remote sensing tool output to measured data

1.1.2 Remote sensing of plantation water use

To derive near-daily estimates of tree water use at 10 m spatial resolution, and deliver estimates through a cloud-based tool that may present an alternative to the current forest water use accounting tool.

1.1.3 Groundwater recharge in the Lower Limestone Coast

Key aims of the groundwater recharge investigation were:

- Automating groundwater level mapping procedures to develop a documented, repeatable method, as no method is specified for determining the 2004 groundwater levels adopted as a baseline in the current LLC WAP.
- Examining the sensitivity of the binary plantation forest groundwater extraction threshold in the current LLC WAP – the current LLC WAP assumes plantation forests extract groundwater where depth to water is 6 m or less, and the impact of altering this depth on the areas of plantation forest requiring water allocations.
- Exploring the annual groundwater level variability between years and how a given annual map can influence the areas of plantation forests requiring water allocations with a varying binary threshold.
- Examining the impact of using a logged (daily) time series of water depth records against the effects of adopting the less frequent manual data on estimating recharge
- Conducting a series of groundwater recharge estimation approaches across the LLC, including the water balance method, the water table fluctuation method (the approach in the 2019 LLC WAP), the chloride mass balance method and a time series modelling approach. All approaches were undertaken using data from 2004 to 2021, compared and, where possible, uncertainty was evaluated.

1.1.4 Wetland setbacks in plantations

Key aims of the wetland investigation works in this project were to:

- Review definitions for key terms including wetlands and groundwater dependent ecosystems (GDEs)
- Review techniques used to determine if a wetland is a GDE
- Investigate means to assess wetland boundaries and ‘condition’ in the LLC
- Review the prevalence and condition of wetlands in or near plantations forests in the region
- Review wetland management requirements which apply in the LLC region
- Review existing knowledge on justification and benefit of plantation forest wetland setbacks

1.2 A note on reporting

It should be noted that this report is provided as a summary of project objectives, methodologies and results with limited discussion and recommendations. More detailed reporting on each of the four main objectives in Section 1.1 has been provided to project funding partners and may be made available on request to these organisations. Reference details for these more detailed reports are provided in Table 1.

Table 1: References to detailed reporting for each study component

Component	Report reference
Remote sensing	JONES, E. G. & MYERS, B. R. 2023. Initial Development of A Tool For FORest Evaporation at High Resolution (FORETHIR). Adelaide, South Australia, Australia: University of South Australia for the National Institute for Forest Products Innovation.
Ground monitoring	LAWSON, J., MYERS, B., BENYON, R., O'HEHIR, J., JONES, E. G. & HEWA, G. 2023. Optimising the management of plantation, water and environmental assets - Plantation water use estimation using on-ground measurement techniques. Adelaide, South Australia, Australia: University of South Australia for the National Institute for Forest Products Innovation.
Wetland setbacks	MYERS, B., LAWSON, J., O'HEHIR, J., JONES, E. G. & HEWA, G. 2024. Optimising the management of plantation, water and environmental assets – Management of Wetlands in the Lower Limestone Coast Plantations. Adelaide, South Australia, Australia: University of South Australia for the National Institute for Forest Products Innovation.
Groundwater recharge	PARTINGTON, D. & BATELAAN, O. 2023. Optimising the management of plantation, water and environmental assets - Lower Limestone Coast Groundwater Recharge. Adelaide, South Australia, Australia: Flinders University for the National Institute for Forest Products Innovation.

2 Methodology

The following sections provide a brief overview of the methodology for each research component. Detailed methods for each are provided with the full reports noted in Table 1.

2.1 Field monitoring of plantation water use

2.1.1 General approach

Monitoring of plantation water use was undertaken at eight study sites over a period of approximately one year. Monitoring was conducted in two phases, with four sites in each phase. The first four sites were selected with a view to effective calibration of the remote sensing tool. For this purpose, sites with higher and lower estimated water use were targeted in both the *Pinus radiata* (PR) and *Eucalyptus globulus* (EG) plantations in the LLC. These sites were identified using a development version of the Forest EvapoTranspiration at High Resolution (FORETHIR) tool (Jones and Myers, 2023) (see Section 2.2). The next batch of four sites were selected for effective calibration, as well as targeting key questions that have not been resolved by previous studies collected – namely the water use behaviour of plantations where groundwater was estimated to be 6 to 9 m away from the surface. A summary of the selected sites is presented in Table 2.

Table 2: Characteristics of sites where plantation water use was monitored for this project

Site name	Easting	Northing	Monitoring period	Year planted (Age when monitored, years)	LLCWAP Management area	Nearest groundwater obswell (approximate distance from site, m)**	Approximate depth to groundwater (m)
Pine high ET*	478066	5824256	2/10/2020 to 19/10/2021	2008 (12)	Zone 2A	YOU041 (1450)	6.5
Pine low ET	492947	5860847	6/10/2020 to 19/10/2021	1997 (23)	Zone 3A	PEN095 (1250)	6.5
Blue gum high ET	458491	5867060	7/10/2020 to 19/10/2021	2004 (16)	Short	SHT031 (1860)	5.5
Blue gum low ET	458056	5874005	9/10/2020 to 19/10/2021	2005 (15)	Coles	CLS050 (670)	4.5
Benara BEN003	458409	5820053	17/03/2022 to 04/04/2023	2013 (9)	Benara	BEN003 (40)	7.4
Deadmans Swamp	486817	5886868	24/05/2022 to 22/03/2023	2005 (17)	Joanna	JOA027	3.5
Myora GAM078	496586	5804797	17/03/2022 to 20/02/2023	2014 (8)	Glenburnie	GAM078	27
Nangwarry NAN009	485512	5840432	17/03/2022 to 29/03/2023	1993 (29)	Zone 2A	NAN009	7

* Pine high ET site was thinned in April and May of 2020, within 5 months of monitoring commencing
** Groundwater Observation well (obswell) codes are used for South Australian groundwater monitoring wells. Data available from: https://www.waterconnect.sa.gov.au/Systems/GD/Pages/Default.aspx

2.1.2 Water balance measurement

Plantation transpiration, throughfall and rainfall were the key variables used to investigate the water balance at field sites and for calibration of the remote sensing tool. After reviewing available methods for transpiration measurement, SFM1 sap flow sensors (ICT International, Armidale, NSW) were adopted. These sensors use the heat ratio method to measure transpiration, a scientific principle for the measurement of sap flow (or water use) in plants.

2.1.3 Rainfall

Rainfall measurements at each site were derived SILO, a database of Australian climate data produced using the procedures outlined by Jeffrey et al. (2001). Data was cross checked with, and compared with data from weather stations nearest to each site which were operated by the Bureau of Meteorology. Sites included the stations shown in Table 3.

Table 3: Details of Australian Bureau of Meteorology weather stations used to estimate plot rainfall

Station ID	Name	Elevation (m)	Plantation site
026021	Mount Gambier Aero	63	Pine high ET
026025	Penola Post Office	62	Pine low ET BG High ET BG low ET

2.1.4 Throughfall

Throughfall (the volume of water passing through the forest canopy) measurements were recorded using four ground level collectors at each site. Collectors consisted of Ø90 mm PVC pipe collection channels, each 1.5 m in length, proceeding to a 15 L storage container. A photograph of throughfall collectors is shown in Figure 1. The collected throughfall values were compared with the total rainfall to determine the proportion of rainfall that passed through the plantation forest canopy to the ground.

Figure 1: A photograph of throughfall collectors installed at a *Pinus Radiata* monitoring site

2.1.5 Other site characteristics

At each site, nearby groundwater observation wells were used to investigate the current and historic characteristics of groundwater recharge. The nearest groundwater well to each site is shown in Table 2, and in some cases other nearby wells were also investigated. Characteristics of historic recharge were estimated using the water table fluctuation technique as described by (Mustafa et al., 2006). This technique has also been used to approximate recharge across most of the LLC region (Government of South Australia, 2019).

Tree growth was also monitored using banded dendrometers (six trees per site) during the transpiration monitoring period. Trees monitored were generally separate from those fitted with sap flow monitors and were randomly selected within the monitoring plot. A photograph of a banded dendrometer setup on one of the trees with sap flow monitoring is shown in Figure 2.

Figure 2: Photograph of a banded dendrometer on a pine tree which is also fitted with a sap flow sensor

2.2 Remote sensing of plantation water use

This research involved the development of a satellite derived evapotranspiration model, FORETHIR, which was subsequently calibrated using the field monitoring data collected in this project. The methods used to develop and calibrate the tool are summarised in the following sections. A detailed description of the model development and calibration is provided by (Jones and Myers, 2023).

2.2.1 Satellite derived evapotranspiration modelling

FORETHIR, the satellite derived evapotranspiration model developed in this project, is a hybrid model incorporating both vegetation indices derived from surface reflectance, and interpolated climate data, developed by Guerschman et al. (2009). The spectral response of natural land cover – vegetation, bare ground, and open water surfaces – is captured through the Enhanced Vegetation Index (EVI) and the Global Vegetation Moisture Index (GVMI), calculated from atmospherically corrected surface reflectance at different wavelengths. Full details of all processing and parameters are provided by Jones and Myers (2023). The final model uses data from the Sentinel-2 satellite to provide estimates of plantation water use.

2.2.2 Satellite ET calibration

In the evapotranspiration model there are eight free parameters, listed in Table 4, which can be calibrated to optimize the fit between the satellite derived ET and the field datasets taken to represent "ground truth". The sap-flow sensor data directly measures transpiration T_{meas}, however to directly compare to space-based ET an estimate of 'E' is also needed. That is, the ground (open canopy) or treetop (closed canopy) evaporative component is required. Given the ages of the plantation compartments in Table 2 canopy closure is assumed, hence at each field site the component 'E' represents the volume of rainfall intercepted by the forest canopy called RE_{meas} [as described in Guerschman et al. (2009)]. The satellite derived ET can then be compared to the sum of the two ground components ($T_{meas} + RE_{meas}$). Due to the timing of available of data, data from only four of the eight field sites described in Section 2.1 were available for use in calibrating the remote sensing tool in this project.

To produce the calibration dataset, all sap-flow data points on dates that that had a corresponding clear satellite image of the site were used. Any satellite measurements of the corresponding sensor location and date that were cloudy, or had poor pixel quality, were not used. The calibration method used was a full free parameter calibration implemented via the Generalised Reduced Gradient method (Lasdon et al., 1978).

The initial values and constraints for the parameters are given in and are taken from the original MODIS Terra satellite calibration work of Guerschman et al. (2009). The resulting calibrated values of the eight free parameters, that were found to minimize the difference between the measured in the field, and the space-based model from the Sentinel-2 satellite, are given in Jones and Myers (2023). The remaining sap-flow values that were not used in calibration were utilized as a validation dataset.

Table 4: Free parameters optimized in model calibration

Parameter	Function	Initial value	Constraints: minimum, maximum
$k_{c,max}$	Upper bound of crop-coefficient k_c	0.680	0.01, 2
a	Scaling factor for EVI in crop-coefficient function.	14.12	0.01, 50
α	Power of EVI in crop-coefficient function.	2.482	0.01, 50
b	Scaling factor for RMI in crop-coefficient function.	7.991	0.01, 50
β	Power of RMI in crop-coefficient function.	0.890	0.01, 2
$k_{e,max}$	Upper bound of rainfall interception-coefficient k_e	0.229	0.01, 2
k_{rmi}	Slope of linear function: GVMI (independent variable) of EVI (dependent variable)	0.775	-2, 2
c_{rmi}	y-intercept of linear function: GVMI (independent variable) of EVI (dependent variable)	-0.076	-2, 10
a_o	New slope in bias correction.	0	-5, 10
a_l	New y-intercept in bias correction.	0	-5, 10

2.2.3 Missing data infilling

To increase the temporal resolution of the satellite evapotranspiration model from a nominal frequency of 6-daily (weather permitting) to a fixed frequency of daily, a simple infilling method was devised using the underlying relationships between the vegetation indices (EVI and GVMI) and the climate data (potential evapotranspiration and rainfall). A full methodology for this is provided by Jones and Myers (2023).

2.3 Groundwater recharge investigation in the Lower Limestone Coast

The groundwater recharge investigation included four related sub-components of research:

- Automating groundwater level mapping
- Examining the sensitivity of the binary plantation forest groundwater extraction threshold in the current LLC WAP
- Examining the impact of using a logged (daily) time series of water depth records against the effects of adopting the less frequent manual data on estimating recharge
- Conducting a series of groundwater recharge estimation approaches across the LLC

The approach to each is summarised in the following sections. All analyses in the groundwater recharge investigation used the Python programming language (Van Rossum and Drake Jr, 1995). In the interest of reproducibility, transparency and extendibility (Hutton et al., 2016), all analyses conducted are reproducible using Jupyter notebooks (Kluyver et al., 2016) which contain the scripts and mostly Python code for each analysis conducted. Such notebooks can also be readily deployed in the cloud with Google Colab (Bisong, 2019) with access to the raw data as detailed in the groundwater recharge report. Access to these tools is available on request to the authors of this report and with the permission of project partners.

2.3.1 Automating groundwater level mapping

It is important to determine groundwater levels to determine which plantation areas may be extracting groundwater. The current LLCWAP adopts a 2004 groundwater level map as a reference, and there is little information formally documented about how this map was derived. To overcome this, a repeatable procedure was developed to produce groundwater level maps across the LLC for any given year. As part of the objective of spatiotemporal analysis of groundwater levels and recharge estimation, ordinary kriging was employed to generate gridded estimates of groundwater level across the LLC region. The ordinary kriging conducted in this study uses the Python based PyKrige[1]. For groundwater level kriging, the ordinary kriging process was carried out using the mean annual water level calculated from a time series of reduced standing water level data (obtained from the Government of South Australia WaterConnect[2] online resource) from a selection of LLC groundwater observation wells for each year from 2004 to 2022. The selection and location of wells is described more fully by Partington et al. (2023).

2.3.2 Examining the sensitivity of the binary plantation forest groundwater extraction threshold in the current LLC WAP

The current LLCWAP assumes a binary threshold for groundwater access by plantations. To account for plantation water use, it is assumed that plantations located where depth to groundwater (DTGW) is 6 m or less from the surface will extract groundwater and be subject to licencing, while plantations where DTGW is greater than 6 m are not subject to

[1] *PyKrige*. (2022). [Python]. GeoStat Framework. https://github.com/GeoStat-Framework/PyKrige (Original work published 2014)

[2] https://www.waterconnect.sa.gov.au/Systems/GD/Pages/Default.aspx

groundwater extraction licencing. DTGW is determined based on the 2004 groundwater level map. The sensitivity of this binary classification of groundwater extraction was explored using the DTGW maps (from Section 2.3.1) in combination with land use maps to filter for forestry plantations. To determine this sensitivity, it was necessary to examine several threshold values and determine the areas of hardwood and softwood that have groundwater above the threshold. For this analysis, the following were used:

1.) 17 depth to groundwater maps generated from 2004 to 2021
2.) 41 thresholds ranging from 4 to 8 m depth (with 0.1 m increments, e.g. 4.0, 4.1, 4.2 … 7.8, 7.9, 8.0)
3.) assessment of three categories:
    - total forestry
    - softwood
    - hardwood

For each of the 17 DTGW maps, 41 groundwater depth use thresholds, and three forestry categories the following was determined:

1.) total area with DTGW above the threshold, which is calculated as the sum of pixels with DTGW above the threshold multiplied by the pixel area (50 m x 50 m = 2500 m^2)
2.) percentage area above the threshold relative to the total area for the category, which is calculated as the sum of pixels with DTGW above the threshold divided by the total number of pixels for the category multiplied by 100.
3.) deemed groundwater extraction, which uses 1 above and multiplies by the deemed extraction rates provided in Table 4.3 of the LLCWAP. As a static land use map is used without the status of the forestry plantations (i.e., no delineation of when hardwood plantations coppiced after date of declaration), the deemed extraction rates applied were 1.66 ML/ha/yr for softwood and 1.82 ML/ha/yr for hardwood plantations.

2.3.3 Examining the impact of using a logged (daily) time series of water depth records against the effects of adopting the less frequent manual data on estimating recharge

The examination of DTGW is generally based on manual measurements which are typically undertaken twice per year, attempting to measure the highest DTGW (end of summer) and lowest DTGW (end of winter) in a given year. However, it is possible that the peak and trough values are not timed to capture the actual peak and trough. To overcome this, the difference between the manual sampling and higher resolution data logger records available in the LLC were compared visually by plots and the impact of the under- or over-estimated peak and trough measurements were evaluated by determining the impact on recharge estimation.

2.3.4 Conducting a series of groundwater recharge estimation approaches across the LLC

Groundwater recharge assessment forms a key aspect of determining the available water in management areas across the LLC. Four main approaches to estimating groundwater recharge (both net and gross) were undertaken to determine which methods were most effective. These included the water balance method (gridded), water table fluctuation method (at points and across a grid), the chloride mass balance (point) method and finally, time-series modelling of groundwater levels with a software tool, Pastas (point). The methodology for estimating recharge with these different methods is explained fully by (Partington et al., 2023).

2.4 Wetland management in plantations

The key aims of this research activity were defined based on a workshop held with project partners at the University of South Australia Mount Gambier campus (Forest Research Mount Gambier) on 28 June 2019. The workshop aimed to determine the key research needs of plantations managers in the LLC region relating to wetlands and wetland management. Details of the workshop are provided by (Myers et al., 2023). The workshop culminated in six priority research goals:

- Further consultation regarding expectations on a 'tool' to assist with managing wetlands in plantations
- Seek to engage an ecologist for (at least) review and commentary on methodologies and research reporting
- Collate and review existing information regarding wetland condition, value and associated research located in the LLC region
- formally reviewing existing knowledge on justification and benefit of setbacks, with emphasis on plantation forestry
- investigating means to assess wetland boundaries and 'condition'
- Pursuing a case study/s on how condition of wetlands has been affected by setbacks in the SE region

The work for each activity was largely in based on review of available documentation and information sources, and as such this report contains no 'results' from the review detailed by (Myers et al., 2023). A portion of the review activity was also published publicly (Myers et al., 2022). The summary findings of the review activity are however provided in the conclusions and recommendations of this report (Section 5).

3 Results

3.1 Field monitoring of plantation water use

The field data from our first field monitoring exercise showed that the total transpiration at the PR high and PR low sites was 8.4 ML/ha and 4.8 ML/ha respectively, with the difference attributed to plantation density being 1.8 times higher at the PR high ET monitoring site. The total groundwater extraction at the PR high ET and PR low ET monitoring site was estimated to be 4.2 ML/ha and 1.3 ML/ha, respectively. It was notable that both sites had groundwater at approximately 6.5 m depth, slightly greater than the 6 m threshold where groundwater extraction is assumed to cease in the current LLCWAP. This suggests more monitoring should be undertaken at sites where depth to groundwater is greater than 6 m to determine if the water use at these sites may be considered characteristic of water use behaviour, to what depth this extraction may extend to, and what the average extraction rate may be at greater depths.

The total transpiration at the BG high ET and BG low ET sites were 5.9 ML/Ha and 4.1 ML/ha respectively. The reason for the difference in these rates of ET was difficult to determine because there was no clear difference in plantation density or other plantation characteristics. The total groundwater extraction at the BG high ET and BG low ET monitoring sites was estimated to be 2.2 ML/Ha and 0.6 ML/ha. Extraction was expected to occur at these sites because depth to groundwater was estimated to be less than 6 m at each site. Of interest, neither site was extracting at the peak extraction rate assumed by the LLCWAP for a BG plantation, which may suggest a need to revise the peak extraction rate for eucalypt. Alternately, the lower rate of groundwater extraction may be because these sites were older than that assumed as a rotation length by the LLCWAP. Verifying the behaviour of older eucalypt requires more monitoring, especially if older BG plantations become characteristic in the LLC.

Plantation water use data from the first phase of monitoring was successfully used for the calibration of the remote sensing tool, the results of which are reported in Section 3.2. The results of the second phase of monitoring in 2021 to 2022 was reported separately.

3.2 Remote sensing of plantation water use

3.2.1 FORETHIR tool development

The Forest EvapoTranspiration at High Resolution (FORETHIR) tool was developed in the IDL programming language, which can be run through the IDL/ENVI software package produced by Harris[3] . The tool exists as a series of .pro files detailed in full by Jones and Myers (2023), including a master file which is the one in which the user enters their key inputs and then runs, and a series a sub files which are called and run automatically by the master file (all codes must be compiled first). All .pro files can be saved and run from any directory once the IDL/ENVI software package is installed by the user, and they have access to a license. The primary view when opening the master view is shown in Figure 3.

[3] https://www.l3harrisgeospatial.com/Software-Technology/IDL

```
;
;         _-_                 Hello and welcome to FORETHIR.
;    /~~   ~~\                FORETHIR is a tool for deriving FORest EvapoTraspiration at High Resolution.
; /~~           ~~\           This is MACH 1 of the tool and it is still under development.
;{                 }          Please send any feedback, questions or comments to Dr Eriita Jones at eriita.jones@unisa.edu.au.
; \  _-       -_  /           We hope you find FORETHIR's insights useful.
;   ~  \\ //  ~
;_- -   | |  _- _
;  _ -  | |    -_
;      // \\

;;;;;;;;;;;;;;;;;;;;;;;;;;User Input ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;Please input EITHER a bounding box in the form of xmin, ymin, xmax, ymax
;OR the Sentinel spatial tiles of interest for the satelite imagery.
;Make sure that your selection is uncommented before you run the code.

;bbox = [133.51,-24.96,138.0,-26.4]
;bbox = []

tilelist = ['T54HVD']
;tilelist = []

;Please intput the dates of interest in the form of 'year(4)-month(2)-day(2)'.
;Currently the model is restricted to dates within a single year.  You will need
;to re-run the model for successive years.

date_min = '20220101'
date_max = '20220220'

;Please select the directory containing the required import files.
indir = 'E:\Tree-water-use\IDL-import\'

;Please ensure you have unzipped the file "import-files.zip" into the import file
;directory.

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

Figure 3: Screenshot of FORETHIR master program

3.2.2 Calibration and validation of the FORETHIR tool

A comparison between model predictions and the first year of continuously recorded sap-flow data (reported in Section 3.1) which was taken to represent 'ground truth' and utilised for calibration and validation of the satellite derived ET is given in Table 5 and Table 6. A comparison between the observed and satellite derived data is also plotted in Figure 4 and Figure 5. Based on the monitoring data available, there were 109 matching satellite – sap flow sensor measurement points across the four sites. These were not evenly distributed however, as cloud coverage occurred much more frequently at the two PR sites in the south of the LLC region, resulting in each of the BG sites receiving twice the number of days of satellite coverage (clear sky during a satellite overpass enabling a usable image) as the PR low, and over four times as much coverage as the PR high site. The reduced availability of satellite data over the pine sites directly resulted in larger errors in the FORETHIR model over these sites, even after calibration. As shown in Table 5, the RMSE at the PR sites was over 2.5 times greater than at the BG sites due to the lower number of calibration data points reducing the capacity of the model to adjust to and attempt to match the water use behaviour at those sites.

Once the model was calibrated, it was then validated by generating site ET predictions at the dates when satellite images were not captured, with the accuracy of those predictions compared against the field monitoring data. A FORETHIR model prediction was made for each of the 374 days that sap-flow sensor data was gathered at each site. As expected, the model continued to perform best at the two BG sites as shown by the RMSE and median percentage error in Table 6. Table 6 includes the estimated canopy rainfall interception and subsequent evaporation at each site, so that the ground evaporation plus transpiration can be totalled for a more accurate physical comparison with the satellite product of ET (rather than comparing simply to the transpiration that is measured by sap flow meters). The site ET total has an associated error bar, derived from the sap flow meters measurement and model error. By comparing the satellite model ET total across the 374 days of site water use monitoring, to the field measured ET total, the model ET is in agreement with the measured ET at 3 of the 4 sites. Only at the PR high site does the satellite model fall outside of the range of error of the measurement data, as the model well underestimated site water use. When comparing to the site rainfall model, the measured and FORETHIR model both predict recharge at 3 of the 4 sites. At the PR high site the predictions differ as the site measurements predict extraction while FORETHIR predicts recharge.

Table 5: Comparison between measured and model data at matching satellite dates

Site Name	#Matching Dates	Site T error (mm/day)	Modelled ET RMSE (mm/day)	Modelled ET median % error
BG low	41	0.19	0.53	28.1
BG high	40	0.38	0.44	21.8
PR low	18	0.14	1.40	117.2
PR high	10	0.42	1.81	39.4
Across all sites	109		**0.949987**	**26.4134**

Table 6: Comparison between measured and model at matching and infilled satellite dates.

Site Name	#Dates	Site T error (mm/day)	Modelled ET RMSE (mm/day)	Modelled ET median %error	Measured T (mm)	Measured & Estimated E (mm)	Site ET (mm)	Modelled ET (mm)	Modelled BOM Rainfall (mm)	Groundwater interaction [measured, modelled] R = Recharge; E = Extraction
BGlow	374	0.19	0.41	23.5	414.6	56.4	471.0±71.1	531.2	616.0	[R,R]
BGhig	374	0.38	0.50	19.8	599.1	49.1	648.2±142.1	584.5	641.3	[R,R]
PRlow	374	0.14	0.98	43.4	497.7	64.7	562.4±52.4	582.3	621.1	[R,R]
PRhig	374	0.42	1.99	41.9	859.4	140.9	1000.3±157.1	558.3	769.5	[E,R]
Across all sites	1496		**1.15810**	**30.1274**						

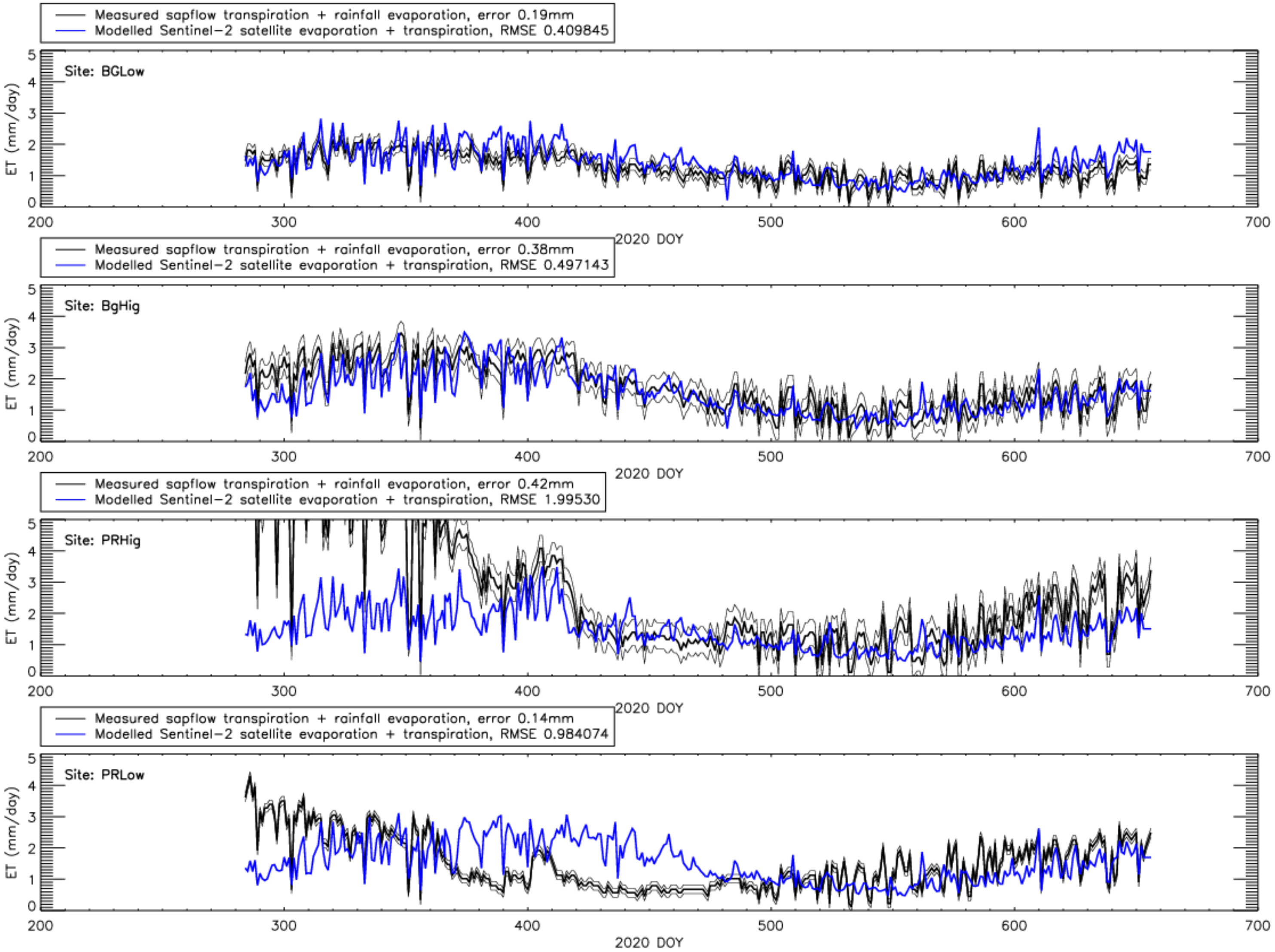

Figure 4: Comparison of daily sap-flow sensor data based ET and and calibrated, infilled satellite model ET estimates at the four calibration sites

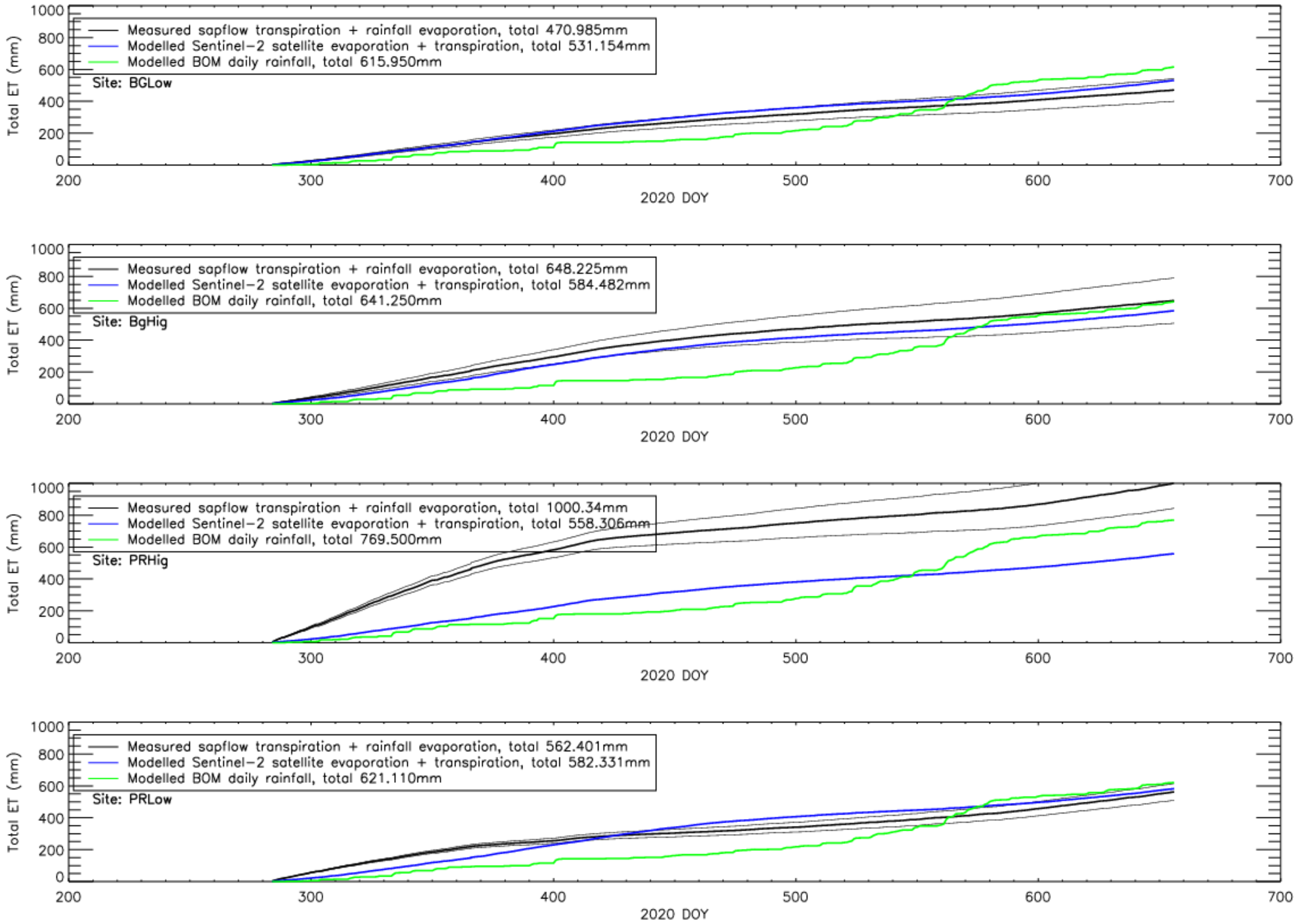

Figure 5: Comparison of cumulative ET at the four calibration sites based on sap flow sensors, canopy rainfall interception, FORETHIR estimation and BOM rainfall.

3.2.3 Comparison to the LLCWAP water accounting estimates

Geospatial data contributed by a range of companies allowed the total water use (sum of ET) and extraction or recharge (difference between total rainfall and total ET) model predictions to be summarised by plantation compartments. This was then compared to the groundwater depth values in 2021. Particular attention was paid to the threshold of 6 m groundwater depth as prior studies [e.g. (Benyon et al., 2006)] indicated that plantations have the potential to extract water within this depth. An extended threshold of up to 9 m threshold was included to assess whether more mature established trees within this proximity to groundwater could also potentially access groundwater, while the areas where groundwater was greater than 9 m depth were considered to be a region where trees are less likely to have significant groundwater access. Table 7 and Table 8 provide the results for all tress, with subsets presented in (Jones and Myers, 2023).

Table 7: Water use rates by groundwater depth - *Pinus radiata* - all tree ages.

DTGW[4]	Number of compartments	Year	Deemed rates of extraction* (ML/ha/yr)	Model rates – total ET mean±σ (ML/ha/yr)	Model rates – extraction or recharge mean±σ (ML/ha/yr)[5]
≤ 6m	1536	2020	**1.66**	5.66±1.34	-0.63±1.11
≤ 6m	1535	2021	**1.66**	6.00±1.50	-0.95±1.33
6-9m	1599	2020	**1.66**	5.25±1.37	-0.97±1.10
6-9m	1596	2021	**1.66**	5.66±1.48	-1.32±1.20
>9m	5165	2020	**1.66**	5.41±1.37	-1.05±1.21
>9m	5164	2021	**1.66**	5.77±1.50	-1.46±1.40

* the rate of groundwater extraction adopted by the LLCWAP for water use by *Pinus radiata* plantations in the LLC

Table 8: Water use rates by groundwater depth - *Eucalyptus globulus* - all tree ages

DTGW	Number of compartments	Year	Deemed rates of extraction (ML/ha/yr)	Model rates – total ET mean±σ (ML/ha/yr)	Model rates – extraction or recharge mean±σ (ML/ha/yr)4
≤ 6m	1116	2020	**1.82**	4.07±1.81	-1.58±1.83
≤ 6m	881	2021	**1.82**	4.08±1.97	-1.98±2.01
6-9m	17	2020	**1.82**	5.01±1.04	-0.48±1.03
6-9m	13	2021	**1.82**	7.13±5.09	-0.55±1.50
>9m	8	2020	**1.82**	4.22±1.50	-1.42±1.68
>9m	2	2021	**1.82**	3.54±2.21	-2.54±2.33

* the rate of groundwater extraction adopted by the LLCWAP for water use by *Eucalyptus globulus* plantations in the LLC

[4] DTW = Depth to Groundwater (m) from surface

[5] Positive rate indicates extraction in alignment with the WAP, while negative rate here indicates recharge.

Softwood plantations were found to have the highest water use when over shallow groundwater tables ≤ 6m depth, a trend observed in both 2020 and 2021. The mean annualised water use rates were generally higher in 2021 than 2020 over all groundwater depth regimes considered. When compared to annual compartment rainfall totals, the mean model values predicted recharge of groundwater over all DTGW regimes considered in the 2020 and 2021 models. Unlike softwood plantations, hardwood plantations were found to have the highest water use when over medium groundwater tables between 6 to 9 m depth, a trend observed in both 2020 and 2021. The mean annualised water use rates were higher in 2021 than 2020, other than the deepest groundwater depth regime considered. Similar to the softwood compartments, although many hardwood compartments were found to be extracting, the mean across all compartments in both the 2020 and 2021 models predicted recharge across the region. A deeper look at the statistics of groundwater extracting hardwood compartments is provided by Jones and Myers (2023).

3.3 Groundwater recharge investigation in the Lower Limestone Coast

3.3.1 Automating groundwater level mapping

Examples for the mapping of mean annual groundwater levels are shown for 2004 (Figure 6) and for 2021 (Figure 7). For each example, the groundwater observation well locations are shown on top of the gridded estimates, which broadly indicate the kriged values of groundwater level match the pattern of observation wells. The associated uncertainty in the kriged values is also shown alongside these maps and indicates that the uncertainty is largest where there are fewer wells (lighter colours). Uncertainty peaks along the coast.

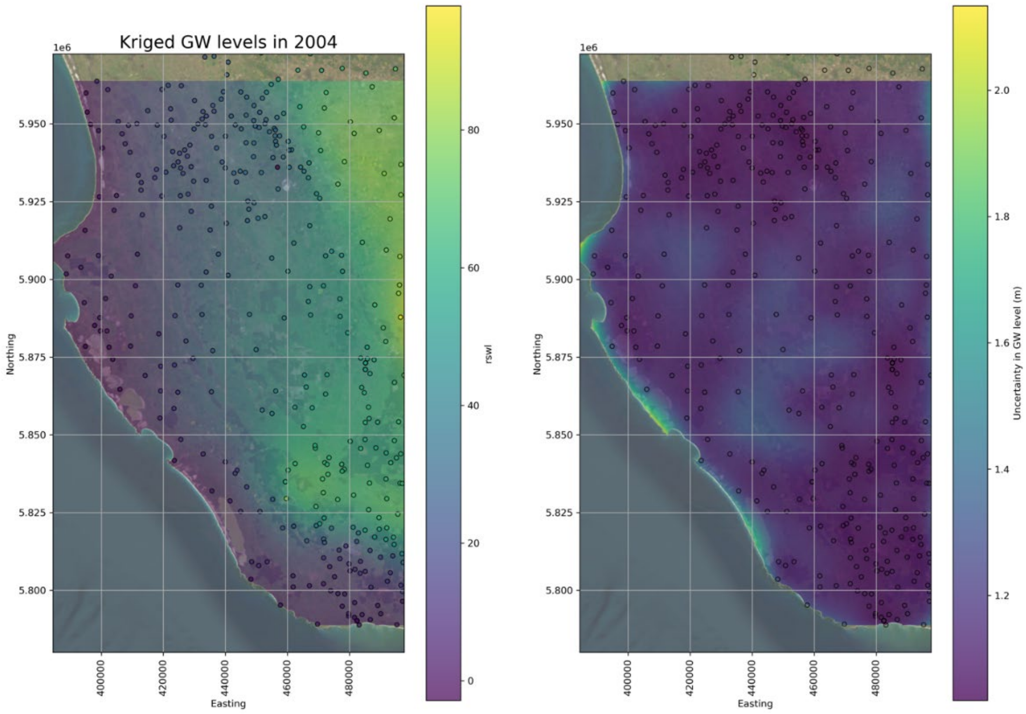

Figure 6: Example of 2004 mean groundwater level mapping and the associated uncertainty. The circles indicate the location of wells used for groundwater levels in the mapping and their infilled colour is the mean groundwater level for 2004.

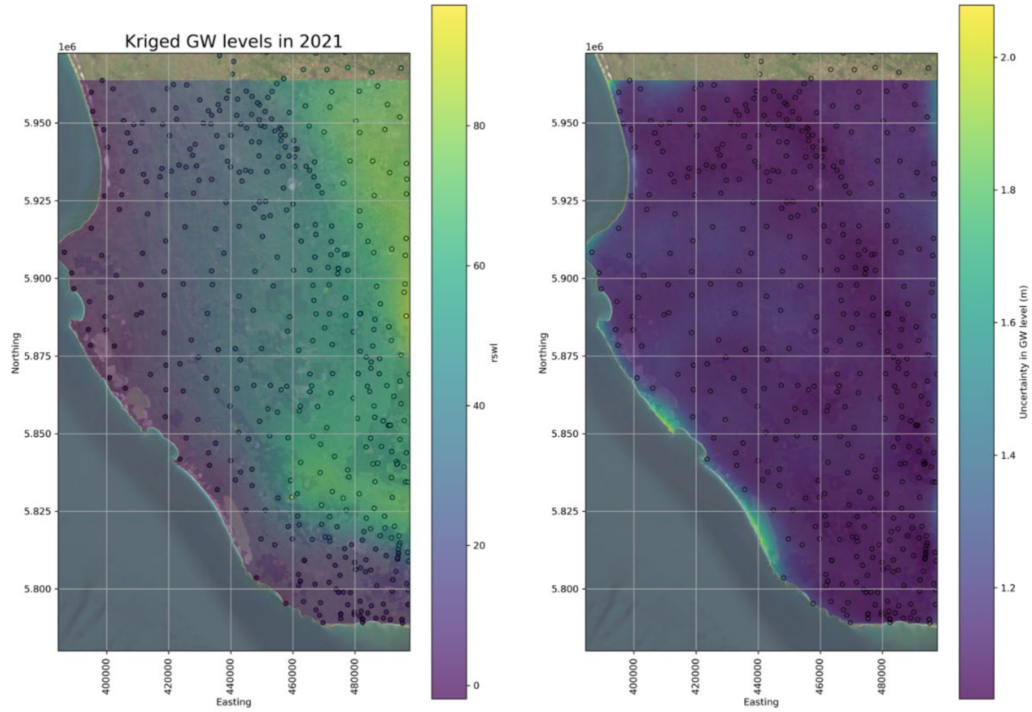

Figure 7: Example of 2021 mean groundwater level mapping and the associated uncertainty. The circles indicate the location of wells used for groundwater levels in the mapping and their infilled colour is the mean groundwater level for 2021.

Using the developed annual mean groundwater level maps, a comparison was made showing the difference between mapped groundwater levels in 2013 (when forestry was brought into the LLCWAP) and more recent groundwater levels in 2021 (Figure 8). In Figure 8a, the blue areas denote increasing groundwater levels, reds denote declining levels and white areas show stable levels. Notably, the management zones of Coles (currently considered a high risk management area due to over-extraction) and Short (currently a medium risk area with due to over-extraction) show increasing groundwater levels from 2013 to 2021. The point-based differences from the wells used in the mapping are shown in Figure 8b, showing point data locations but also highlighting observation wells that had data available only in 2013 and 2021, but not in both years.

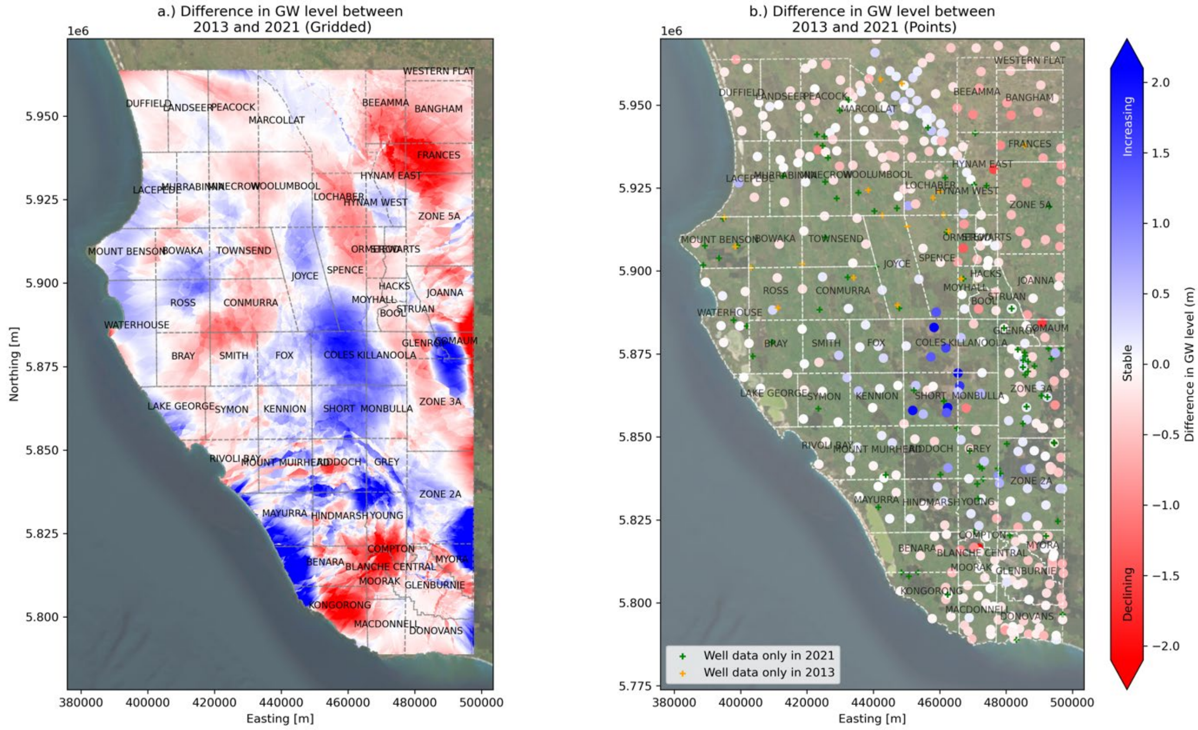

Figure 8: Example of the difference between mean annual groundwater levels from 2013 (when forestry was included in the WAP) and 2021. The reds indicate a decline in groundwater levels since 2013, the blues indicate an increase, and the whites indicate stable groundwater levels. The gridded difference based on the kriged maps of groundwater level produced is shown in a.), and the point-based differences in groundwater level where both wells had data in the given years are shown in b.). Also shown in b.) are the points from 2013 and 2021, which did not have groundwater levels and could not be used for point comparison.

3.3.2 Examining the sensitivity of the binary plantation forest groundwater extraction threshold in the current LLCWAP

The sensitivity of the singular threshold (currently adopted at 6 m depth) for determining which areas of forestry are extracting groundwater is shown in Figure 9, with lines indicating all years from 2004 to 2021 (only 2004 and 2021 are highlighted with different marking). It can be seen from Figure 9a that for all forestry in 2004 (denoted by the dashed line), there is a near linear relationship between area of forestry using groundwater and the adopted groundwater extraction depth threshold. However, in other years a non-linear relationship is apparent. This highlights that the use of 2004 depth to groundwater as a reference level yields the highest groundwater use as compared to all other years from 2004 to 2021. The results also indicate that increasing the depth threshold to levels greater than 6 m does not tend to capture much greater areas of hardwood, but does capture greater areas of softwood. Furthermore, the groundwater use for softwoods based on the 2021 depth to groundwater map shows the smallest area of extracting plantations and hence suggests the smallest groundwater use if adopting the binary threshold.

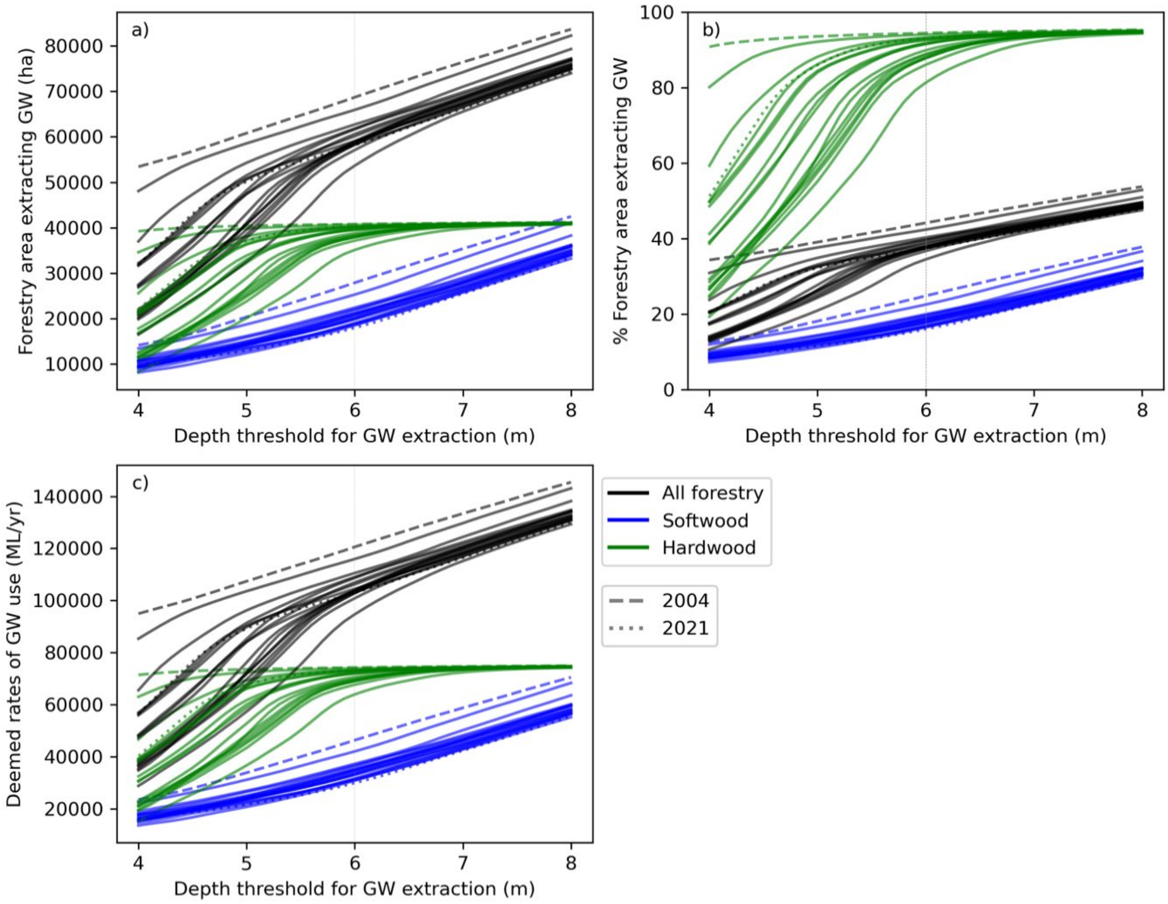

Figure 9: Area of plantation forestry that suggests groundwater extraction based upon a depth to groundwater threshold for thresholds ranging from 4 to 8 m deep. Each line indicates a particular year, 2004 and 2021 are specifically indicated. (a). The corresponding percentage area of plantation forestry that has access to groundwater for different thresholds for groundwater extraction (b). Also, the corresponding total deemed rates (hardwood=2.5 ML/ha/yr, softwood=1.2 ML/ha/yr)) for different groundwater use depth thresholds (c).

3.3.3 Examining the impact of using a logged (daily) time series of water depth records against the effects of adopting the less frequent manual data on estimating recharge

Figure 10 shows the difference between sparse manual sampling and high-resolution data loggers of groundwater level at observation bore MAC046. The differences highlight that in some years, the capacity to capture the minimum and maximum levels is poor (e.g., 2016) and a little better in other years (e.g., 2018, 2019). However, these average differences, as highlighted by the dashed lines in Figure 10b, are almost 0.25 m more for the data loggers. As might be expected, this shows that manual sampling always underestimates the actual fluctuations in depth to groundwater.

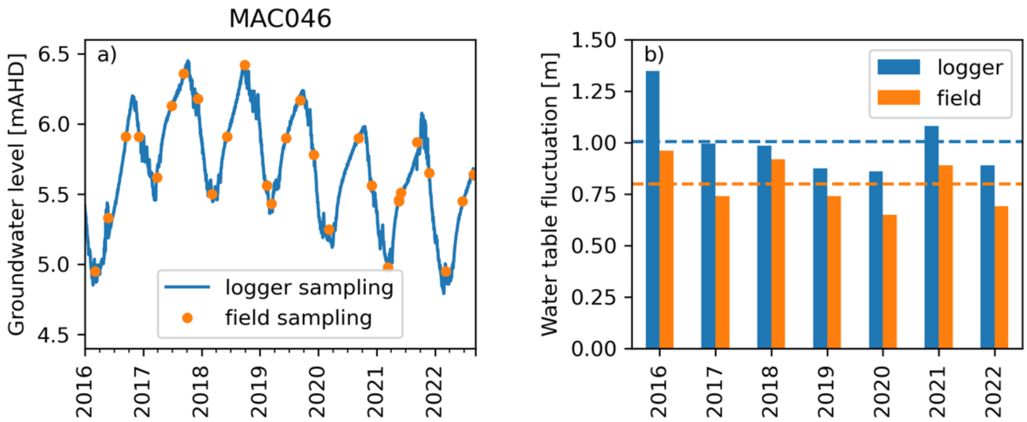

Figure 10 a): Comparison of logger and field sampling at well MAC046 and b): highlighting how peak and minimum groundwater levels differ when field measurements are taken 3-4 times a year versus continuous groundwater level data loggers.

In considering nine of the data loggers that had at least two years of consecutive data and by calculating the average difference in water table fluctuations, it is possible to determine the extent to which recharge is underestimated with the water table fluctuation method (assuming all assumptions are valid, and that the error lies only in the fluctuation). The results show recharge underestimation with manual readings of groundwater level for the nine selected bores when using a specific yield of 0.2. The underestimation ranges from 17 to 95 mm/yr.

3.3.4 Conducting a series of groundwater recharge estimation approaches across the LLC

Aggregate results at the level of unconfined groundwater management zones are presented here for the different recharge estimation approaches, including the gridded water table fluctuation, point based water table fluctuation, chloride mass balance, water balance, and point-based Pastas time series models. Herein, the focus is on selected management zones that have forestry allocations greater than zero (not including farm forestry), as listed in “Table 1” of the LLCWAP Appendix (Government of South Australia, 2019). The selected management zones are shown in Figure 11, which also highlights the status of the zones as published by the LLC Landscape Board (accessed in December 2022). Of the medium- and high-risk zones, all have licenced forestry activities except for the Frances management zone.

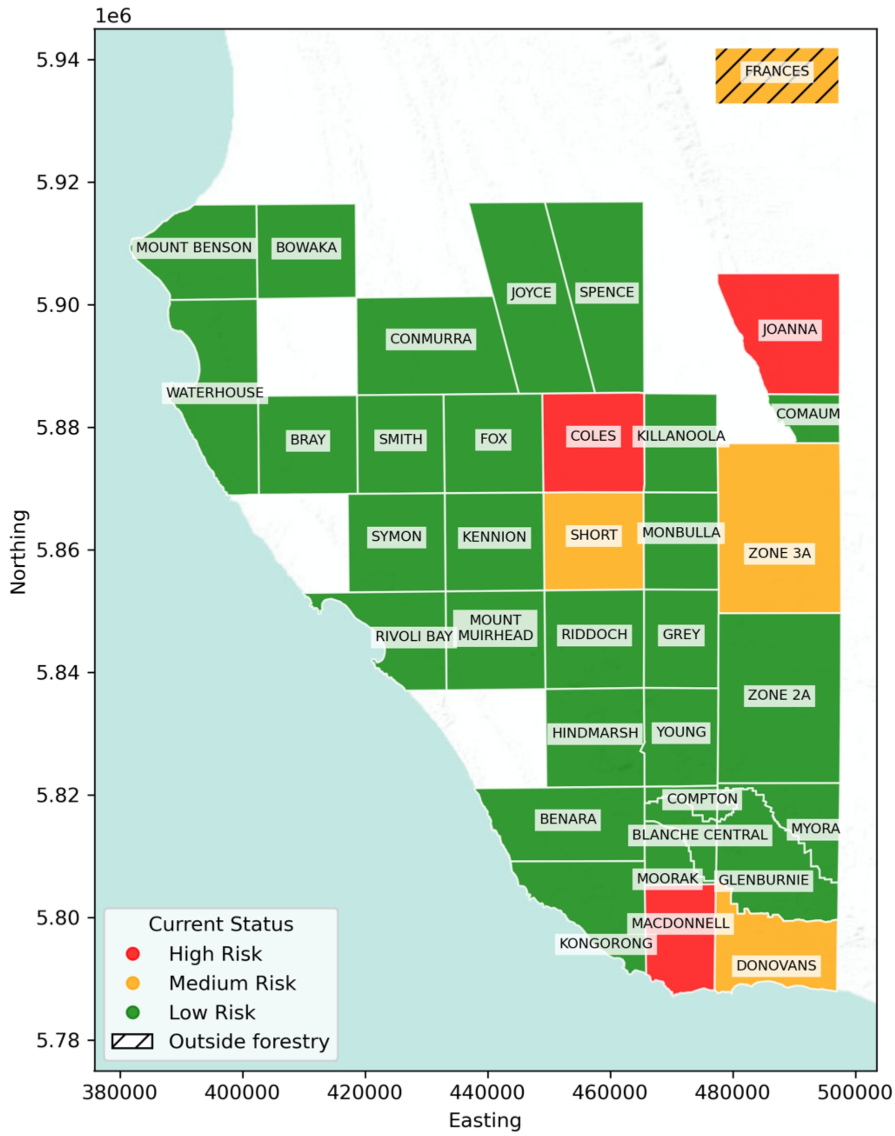

Figure 11: Management zones with forestry allocations greater than zero and current status of unconfined management zones from the Limestone Coast Landscape Board[6]

A summary of estimated gross recharge alongside adopted recharge for the WAP is provided for the whole LLC and "at-risk" management zones in Figure 12. The various methods of recharge estimation provide a broad range of gross recharge values but also have some large associated uncertainties. In general, the largest gross recharge values were obtained from the Pastas approach, whereas smaller gross recharge values were obtained from the chloride mass balance approach. The estimates from the point and grid-based water table fluctuations had the most similarities, as might be expected, but the point-based approach had larger uncertainties associated with the estimates.

[6] https://www.landscape.sa.gov.au/lc/water-and-coast/water-allocation-plans/lower-limestone-coast/lower-limestone-coast-management-areas

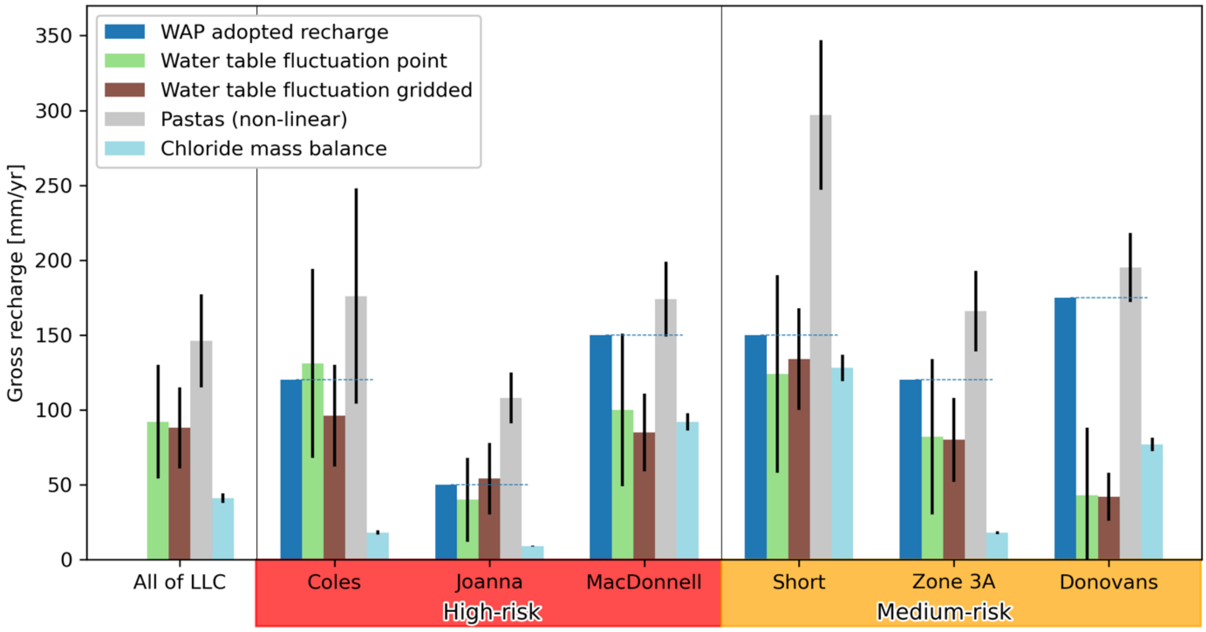

Figure 12: Comparison of aggregated gross recharge from different methods in this study across the whole LLC and in the high- and medium-risk unconfined groundwater management zones. The vertical black lines on each bar indicate the uncertainty estimates, and the horizontal dashed blue lines extend the LLCWAP adopted recharge value to aid comparison with other methods.

A summary of net recharge across the LLC and for the high-risk unconfined groundwater management zones is provided in Table 9. The net recharge indicates whether the area of interest is gaining or losing water on average. The water balance method shows that for five of the six management areas of concern, only one is net extracting groundwater and that the others seem to be net recharging on average over the period from 2005 to 2022. The uncertainty in the estimation of net recharge for the gridded inter-annual water table fluctuation method is large enough to make it hard to predict whether an area is net recharging or extracting groundwater from the unconfined aquifer. The results from some Pastas models have low confidence due to extreme values and poor fits to data which were deemed unsuitable for providing estimates in some unconfined groundwater management zones.

Table 9: Comparison of net recharge from different methods in this study across the whole and in the medium and high-risk unconfined groundwater management zones

Recharge method	Water Balance (P – ET) [mm/yr]	Water table fluctuation inter-annual [mm/yr]	Pastas (linear) [mm/yr]
Type	Net	Net	Net
Spatial	Gridded	Gridded	Point based
All of LLC	38 ± 10	-5 ± 15	180 ± 118
Coles	17 ± 9	-12 ± 15	*N/A
Joanna	-24 ± 9	-2 ± 18	317 ± 63
MacDonnell	84 ± 12	-4 ± 12	175 ± 122
Short	47 ± 9	-3 ± 14	6 ± 255
Zone 3A	31 ± 10	-10 ± 18	183 ± 110
Donovans	94 ± 11	-3 ± 8	*N/A

* No suitable models in management zone for recharge estimate

4 Discussion

4.1 Field Monitoring of plantation water use

4.1.1 *Pinus radiata* sites

The data suggests that trees in the first phase of monitoring were extracting groundwater at a depth just above the current 6 m threshold. However, it should be noted that this finding has several complications. First, at the PR low site (which was not recently disturbed by thinning), the extraction was much lower than the peak value. Second, the estimated depth to groundwater was based on topography and the water level in the nearest groundwater observation wells, which were over 1.2 km away from both pine monitoring sites. Measurements from a monitoring bore on site would provide a much better measure of the depth to groundwater. Finally, the data from the PR high site appears to be complicated by a recent thinning operation. The data suggests that there was a relatively high rate of water use in the summer months following the thinning, and this may or may not represent normal conditions post-thinning. For example, in models underlying the deemed rates applied in the LLCWAP which were developed by Harvey (2009), there is an assumed drop in water use in the two years following thinning operations for pine plantations. Based on this finding, more data should be collected at the PR high site to determine a typical 'peak' value of extraction at this site. It is also suggested that more research is warranted into the water use behaviour of trees immediately post thinning, and how characteristic the relatively high water use at the PR high site after thinning might be for other pine sites immediately after thinning.

4.1.2 *Eucalyptus globulus* sites

The total transpiration at the two BG sites using the sap flow meters was 5.9 ML/ha at the BG high site and 4.1 ML/ha at the BG low site. Thus, transpiration at the BG high site was 1.5 times higher than the BG low site based on the measured sap flow records. Groundwater extraction was estimated to be 2.2 ML/ha at the BG high site, over 3.9 times higher than the 0.6 ML/Ha estimated for the BG low site. Unlike the case for pine, the reason for this difference was harder to determine. Groundwater was less than 6 m away from the surface at each site so some extraction may have been anticipated. However the BG high site was estimated to be 5.5 m above groundwater (based on a well 1.8 km away) compared the BG low site where water was estimated to be shallower (4.5 m based on a well 670 m away). The trees were both mature and of similar age (the blue gum high ET planted in 2004 and blue gum low ET planted in 2005) suggesting little or no age related impact, and both sites had a similar density. Other variables which affect the estimate may be the variability of rainfall from site to the nearest gauge, noting that the distance from nearby rain gauges was similar.

The peak groundwater extraction assumed to occur for mature eucalypt plantation by the LLCWAP is 3.64 ML/ha/year (identical to pine) which reduces to an annualised value or 'deemed rate' of 1.82 ML/ha/year when applied in a life cycle model developed by Harvey (2009) that takes into account year of planting and gradual increase to this peak extraction rate in the first seven years of an 11 year cycle. It is notable that both sites were extracting groundwater at lower values than this peak extraction rate. On the surface, this may suggest a reduction in the peak extraction rate for eucalypt be considered based on these two sites alone, however the situation is more complex. Both these sites are older than the 11-year lifespan of a plantation assumed by Harvey (2009) (they were approximately 16 years old when monitored), and as such the reduced extraction may be because of this maturity, which should be a subject of future investigations.

Interestingly, since both BG sites were in ground longer than anticipated by the ‘deemed rates’ model by Harvey (2009), we applied the deemed rates model to the blue gum high ET site to see what the impact of taking the measured extraction rate of 2.2 ML/ha/year into the model as a peak extraction rate over an assumed 18 year lifespan. The resulting annualised water use was 1.56 ML/ha/year. It is notable that this is still lower than the deemed rates for eucalypt (1.81 ML/ha/year) however more evidence would be required to test whether the highest extraction rate we estimated is characteristic of eucalypt plantations from year 7 onward, or if the lower extraction rate we measured also characterises these same plantations in their later or earlier years. Data on the age of eucalypt across the South East of SA should also be examined to see how characteristic these older plantations are in coming years. Based on communication with forest growers, it is understood that these older plantations are in ground longer due to wood processing and export delays affecting the timing of harvest, and this is not expected to be a long-term phenomenon. The implications of these findings are, however, that neither plot was extracting at the peak rate warranting further investigation.

4.2 Remote sensing of plantation water use

The FORETHIR model makes several predictions that differ from those of the LLCWAP water use models. These can be summarised as follows:

1. In general across the region in both 2020 and 2021 the predominant trend for both softwood and hardwood plantations is one of recharge based on this phase of the FORETHIR model development.
2. In both 2020 and 2021 the rates of extraction for both softwood and hardwood plantations are generally significantly lower than the deemed rates of the LLCWAP. FORETHIR predicted a mean rate of 0.30±0.23 ML/ha/yr extraction for 11-12 year hardwood over shallow groundwater ≤6m depth, significantly less than the deemed rate of 1.82 ML/ha/yr. For softwood the prediction was a mean 0.66±0.53 for plantations in their peak extraction phase of their lifecycle, again still significantly less than the deemed rate of extraction of 1.66 ML/ha/yr.
3. The total water use rates, and rates of extraction, were generally greater amongst softwood than hardwood, in contrast to the deemed rates of the LLCWAP.

Firstly, a caveat must be given for the interpretation of the annualised water use rates and groundwater extraction or recharge rates. The quality of these summary statistics – mean and standard deviation – are strongly contingent on the integrity of the GIS data provided. The spatial data was queried for compartment attribute descriptors such as ‘planted’ versus ‘fallow’, ‘stocked’ versus ‘unstocked’, ‘productive’ versus ‘unproductive’, ‘harvested’ etc. Where appropriate, compartments that were unplanted were removed from the analysis so as not to skew statistics and bias the model rates (as these compartments would have very low annual water use and high recharge and would therefore reduce estimated water use and extraction). However not all attribute data was accurate - for example, some compartments were labelled as ‘fallow’ when they were found to be clearly stocked and so could not be removed. Furthermore, some compartments had no planting attributes that could be interrogated. Therefore, it is likely that there are unstocked or harvested compartments involved in the geospatial analysis that have reduced the overall annualised mean model rates and mean extraction predictions.

In response in point 1 above, this may at first seem an unusual prediction as it is not expected broadly across the region. This finding may be a result of the quality of GIS data as discussed above. Secondly, the comparison with sap flow data shows that the model is highly accurate in its daily water use and its annual water use totals at 3 of the 4 field monitoring sites used for calibration and validation, but that due to cloud coverage limitations it has lower accuracy for softwood than for hardwood plantations at present. The model may therefore have a built in bias both towards higher accuracy for hardwood, and for predictions of recharge, or rather towards under-predicting total water use. These biases can only be rectified by a greater breadth of calibration data that captures a greater range of softwood plantation sites and extracting compartments. Nevertheless, the high accuracy of the model at the 3 out of 4 calibration/validation sites indicates that it can be applied, with caution, to inform decisions on the potential water use of the greater region within the error bars supplied.

In response to point 2 and 3 above, Figure 14 compares the annual water use rates for softwood and hardwood compartments that were found to be extracting, both all ages and those 11-12 years only. This figure illustrates two of the key discrepancies between the FORETHIR predictions and the LLCWAP deemed rates across the region. A key contributor to the increased rates of plantation water use observed across many compartments in the 2021 FORETHIR model compared to the 2021 model is the increased rainfall received across the region in 2021. The higher rainfall totals of the 2021 interpolated cumulative rainfall model compared to the 2020 model are supported by BOM weather station data e.g. see monthly totals at Mount Gambier in Jones and Myers (2023). The model predictions – both the numerical rates of plantations water use, and the interpretations of potential recharge or extraction that are derived from them - can only be interpreted within the context of the error margins. As a broad summary, the model is more accurate for hardwood than it is for softwood, due to the greater number of matching satellite-calibration data points at hardwood sites. The error on the cumulative annual ET total at the pine validation sites can range from ± 52-157mm/year or 42-44% median error on measurement. The error on the cumulative annual ET total at the blue gum validation sites can range from ± 71-142mm/year or 19-23% median error on measurement. The error on the cumulative annual rainfall total is unknown and therefore an error on the total rates of plantation water use cannot be calculated, but may be expected to fall in the range of 20-40% given the magnitude of error on ET.

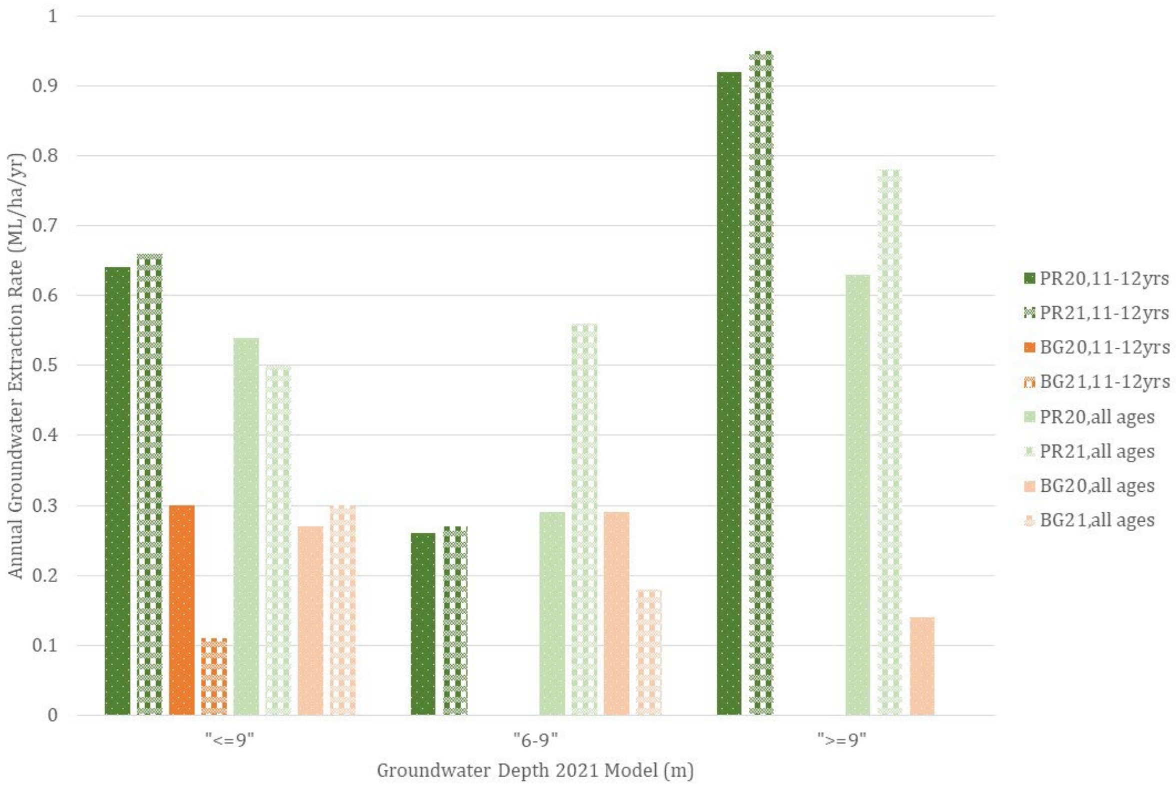

Figure 13: Estimated rate of groundwater extraction for hardwood *Eucalyptus Globulus* and softwood (*Pinus Radiata)* with tree age

4.3 Groundwater recharge investigation in the Lower Limestone Coast

The varied approaches to gross and net recharge estimation in the LLC demonstrated the large variability in recharge estimates across methods and large uncertainty within methods. All the methods used for recharge estimation and the way they were implemented have some desirable aspects and some areas for concern that warrant continued improvement and that demand communication of their limitations. Detailed discussion is provided by (Partington et al., 2023), but a summary of points is provided below.

4.3.1 Data sources

There are many products for which there are no uncertainties provided along with the products, e.g., rainfall, potential and actual evapotranspiration. In this work, we have employed only a single product (subjectively chosen as the most reliable) but acknowledge that there are other products for each available, and in the absence of uncertainty products, there would be a benefit in applying multiple products to develop an ensemble to get a better estimate of uncertainties and variability across products.

4.3.2 Spatiotemporal analyses

In our spatiotemporal analyses, ordinary kriging was the chosen approach to generate gridded products from the point data for groundwater levels, groundwater level fluctuations and specific yield, in part to keep consistency with previous mapping exercises of groundwater levels performed by the DEW. While this was a favourable approach to employ in this work, the actual fit between observed and nearest grid point values could have been improved, e.g., by restricting the range in the semivariogram, although this would have left a poorer fit of the data to the semivariogram.

4.3.3 Methods for estimating recharge – Water balance method

There was no uncertainty estimation for the water balance method at the pixel level due to a lack of accompanying uncertainty products for the gridded rainfall from SILO and the AET from the CMRSET2.0 dataset. It has been established that such products can have large uncertainties, and differ significantly across different products, e.g. between the SILO, BoM and AWAP rainfall products. There exist large differences at particular locations due to the different methods for gridding from the sparse rainfall observation data (Fu et al., 2022, Tozer et al., 2012). It would be beneficial to obtain uncertainty products for both the BoM rainfall and CMRSET2.0 AET to allow error propagation through the water balance approach.

Despite these limitations, the water balance method provides high temporal and spatial resolution (which can be even finer than applied in this study), providing recharge dynamics, which can be particularly useful in studying land-use aspects. It would be interesting to explore the consistency of these estimates with overall groundwater dynamics from observation wells or associated gridded products to determine if there is a mismatch (e.g., water balance showing net recharge but observations wells showing declining groundwater levels) and, if so, why.

4.3.4 Methods for estimating recharge –Water table fluctuation

The LLC WAP made use of the water table fluctuation method in determining adopted recharge estimates for each unconfined groundwater management zone. The adopted recharge estimates were based on groundwater time series that ended in 2005 and using a selection of wells that was not publicly documented. In applying the point-based approach to a large number of observation wells using the same selection as used in the water table mapping exercises and using updated data from 2005 to 2022, recharge was less compared to the LLC WAP from 2019 for all medium and high risk zones except for Coles in which it was higher. For both the point-based and gridded intra-annual water table fluctuations, the aggregated gross recharge at the management zone level were similar with similar magnitudes of uncertainty. In both the point-based and gridded intra-annual water table fluctuation approaches, there were sometimes large water table fluctuations (> 2 m) in the data that were not automatically removed or smoothed and could cause big changes in the recharge estimates. It is worthwhile to determine the causes of such large changes, which were likely due to pumping but should have such years removed from this analysis.

4.3.5 Methods for estimating recharge - Chloride mass balance

Overall, the chloride mass balance approach to gross recharge estimation provided estimates much lower than the other three approaches and were also somewhat difficult to compare due to the long-term integration of chloride that they represent. A comprehensive discussion of the challenges of applying the chloride mass balance method is covered by (Crosbie et al., 2015).

4.3.6 Methods for estimating recharge - Time-series modelling

The time-series modelling approach to recharge estimation was the most complex of the methods employed, and while the results showed promise, there are still some challenges to be overcome in automating the generation of the 547 groundwater level and recharge models. Detailed discussion is detailed by (Partington et al., 2023)

4.3.7 Overall assessment

For each of the recharge estimation methods employed, their implementation was relatively straight forward, with the Pastas model the most complex, but they are much simpler than building a numerical groundwater model and significantly faster. The use of scripting (Python programming) for conducting these methods allowed for repeatable workflows, which makes these results not only reproducible but also allows for reassessing input data (e.g., choice of wells) and expanding or contracting the dataset as desired. The variability in recharge estimates across approaches highlights the importance of using multiple methods as each has its own limitations and sources of uncertainty.

A very important and often-overlooked aspect of all these recharge analyses is the time period examined, especially under a changing climate and with varying land uses. There is a question of suitable windows for determining averages that are meaningful in the context of forward planning for water allocations. For example, throughout this groundwater recharge study, we have utilised the window from 2005 to 2022, however, this may not be a good predictor for future recharge, depending on the climatic cycles captured. The five-year basis of the water allocation plans is also tricky as there is every possibility that climate driven declines in groundwater can occur over a 5-year period (e.g., in a period dominated by El Nino) that will later recover (e.g., in a period dominated by La Nina).

Finally, recharge is spatially varying due to variability in hydroclimatic forcing, land cover and soil types, which is why trying to capture the spatial variability has merits and why applying single or only a few point estimates over larger areas can lead to less informed estimation of recharge.

5 Conclusions and recommendations

5.1 Field monitoring of plantation water use

Sap flow meters were successfully implemented at four pine and blue gum plantation sites. The sites were originally selected using an early, development version of the FORETHIR tool and represented areas estimated to have higher and lower ET for these plantation types across the South East of SA. Site data was collected for a period of two years (one year is reported here) and was suitable for use in calibrating and verifying the remote sensing tool.

The data showed that the total transpiration at the pine sites was 8.4 ML/Ha and 4.8 ML/ha, with the difference attributed to plantation density being 1.8 times higher at the PR high monitoring site. The total groundwater extraction at the PR high and PR low site was estimated to be 4.2 ML/Ha and 1.3 ML/ha. It was notable that both sites had groundwater at 6.5 m depth which was just above the 6 m threshold currently assumed by the LLCWAP, and this suggests more monitoring should be undertaken at sites where depth to groundwater was just above 6 m to determine if the water use at these sites may be considered characteristic of water use where depth to water is just above 6 m, to what depth this applies, and what the average extraction rate is at this and greater depths should it occur.

The total transpiration at the BG sites were 5.9 ML/Ha and 4.1 ML/ha respectively. The difference in these rates was difficult to determine because plantation density was not a clear difference in the site characteristics. The total groundwater extraction at the BG high and BG low sites was estimated to be 2.2 ML/Ha and 0.6 ML/ha. While groundwater was estimated to be at a depth of less than 6 m at each site, neither site was extracting at the peak extraction rate adopted for a plantation, which may suggest a need to revise the peak extraction rate for eucalypt, or alternately, may be because older plantations characteristically use less, again indicating a need for more investigation.

- Based on these findings, the following recommendations are made:
- The PR high site had ET values greater than the current assumptions in the LLCWAP which may be because of recent thinning. More data should be collected at the pine high ET site to determine a typical 'peak' value of extraction at this site without recent interference.
- Based on the results for the PR high site, more research is warranted into the water use behaviour of trees immediately post thinning, and how characteristic the relatively high water use at the pine high ET site after thinning might be for other pine sites immediately after thinning – is this behaviour an outlier response or does water use temporarily increase in all cases? Could the water use behaviour be impacted by the season when thinning occurs, or by association, weather conditions that occur during or after thinning?
- The data suggests that groundwater was extracted at both pine sites where depth to groundwater was estimated to be 6.5 m, a level slightly above the depth threshold, but extracting groundwater at a rate much lower than the currently applied extraction rate in the LLCWAP. It is recommended that water use monitoring should continue to occur at pine and eucalypt plantation sites where groundwater is close to but greater than 6 m (suggest 6 to 9 m). It is important to determine whether extraction is likely to occur at most sites where groundwater is at depths greater than 6 m, and if so, how the rate compares to the currently adopted peak rate of extraction for pine trees (3.64 ML/ha). Such sites should ideally be situated much closer to, or incorporate

within them, their own groundwater monitoring wells and rain gauges to reduce the potential for error around the depth to groundwater and rainfall data.
- There was a difference in the water use observed at the two blue gum plantation monitoring sites which should be further investigated because sites were of a similar age and density, and there was no other immediately obvious explanation for the difference. Investigations could consider (for example) site soil quality at each location which may affect the water use of trees; investigating the presence of clay in layers beneath the monitored point of the plantation which may be impeding groundwater extraction at the blue gum low ET site; or examining data related to the presence of pests or disease which might be hampering the health of trees and reducing (or increasing) water use at either site. Interrogation of LIDAR growth modelling data might also inform whether growth patterns are similar (as suggested by site measurements) at each site at the broader compartment level.
- Both blue gum sites were using less water than the currently assumed peak groundwater extraction rate adopted by the LLCWAP. This may be because of the age of the plantations (approximately 16 years) or the site characteristics. It is important that more eucalypt sites with an age of less than 11 years are monitored to ensure that the currently assumed peak extraction rate of 3.64 ML/ha/year is not over estimated.
- It is known that there are several older eucalypt plantations in the LLCWAP region and it is suggested that industry consider if longer rotations than those assumed by the LLCWAP (11 years) are going to occur into the future for some plantation sites. If so, the water use of these older sites should be investigated to better understand the water use of mature blue gum plantations to avoid the extrapolation of the existing 3.64 ML/ha/year across all sites and show evidence of a more fair and accurate estimate of water use for extended life cycles.

5.2 Remote sensing of plantation water use

The Forest EvapoTranspiration at High Resolution tool – FORETHIR – is a plantation water accounting tool for the forest industry. It provides quantitative measurement of plantation total water use, and rates of groundwater extraction and recharge, with associated error bars, for both hardwood and softwood plantations. FORETHIR provides daily forest water use products at 10m x 10m, making it higher spatial and temporal resolution that other products available to the industry. It currently has an accuracy of *0.4-1.8 mm/day RMSE* making it on par with the national product CMRSET, but greatly improves upon other models in its spatial and temporal resolutions. When applied to 2020 and 2021 data FORETHIR finds that, even within the model error, the rates of extraction for both softwood and hardwood plantations are generally lower than the deemed rates of the LLCWAP and significant areas of recharge are predicted to occur across the region, consistent with the findings of other methods. FORETHIR provides much more than just water accounting. It also provides rich information on forest and forest ecosystem health, and provides actionable insights on forest-groundwater interactions at high frequency (daily) and high resolution to forest managers and industry stakeholders.

Based on the findings and discussion contained in this report the following recommendations are made:
- Expanding the field monitoring sites to capture greater variety of plantation environments, namely more sites in softwood, and over depths to water between 6-15m for the purposes of calibration and validation of the forest water use model. This would result in a reduction of error and increased reliability of FORETHIR and

develop the understanding of the potential for forests to extract groundwater at depths greater than 6 m.
- Investment in the application of FORETHIR ET and extraction/recharge products for forest health and stress monitoring, groundwater-forest interactions, and bushfire risk and severity forecasting.
- Opening up the potential access to the tool by porting the tool into an open source software environment (e.g. Python) rather than the currently applied commercial programming environment (IDL) that requires licencing for access and application.

5.3 Groundwater recharge investigation in the Lower Limestone Coast

Estimating both gross and net recharge is a crucial part of water balance accounting but is also highly uncertain, as has been highlighted previously (Crosbie et al., 2015) and demonstrated for the LLC in this work across all recharge estimation methods. Furthermore, the hydrological fluxes related to gross and net recharge - estimates of plantation forest water use (soil water and groundwater) and recharge interception – are similarly uncertain. The water balance approach suggests areas where plantation forests appears to be net recharging but where it also is within 6 m of the water table, which contrasts the deemed rates approach. As the LLCWAP water balance components are based on long term behaviour (or averages), using snapshots of groundwater levels from a particular year in calculations, it misses the important inter-year variability in groundwater levels and hydrological forcing.

For gross and net recharge estimation, there are several ways that the employed methods could be improved. From a methodological standpoint, we provide some suggestions to enhance these approaches:

- for spatial analyses, utilise dynamic spatial data sets rather than static land use and water course / water feature data sets. This should leverage the Digital Earth Australia Land Use and Water Observations from Space. This would allow better assessment of land use types for temporal mapping exercises as well as inform individual well assessments.
- For future projections, utilise the BOM Australian Water Outlook to gain an ensemble of rainfall and potential evapotranspiration.
- For the specific yield uncertainty, we recommend applying the approach presented in Crosbie et al. (2019) to better capture the point uncertainty rather than the geostatistical approach used within this study.
- Advocate checking consistency of water table fluctuation and water balance methods

In terms of the use of groundwater depth maps, it was clear that there is a lot of variability over the period from 2004 to 2022. As such, it is recommended to advocate to avoid the use of snapshots from a particular year of groundwater levels across the LLC region as representative. It would instead be more robust to use averages of longer time periods (5, 10 or 20 years) unless reporting on the state of the resource at a particular time. This has a large impact on the volume of water use being estimated in the deemed rates, which may tip the scales in terms of allocation status.

It is also recommended to advocate for updating the adopted recharge values determined using the water table fluctuation method considering the level of over-estimation. To allay some of the concerns raised in the water table fluctuation method from sparse sampling, recharge estimation could be improved with increased use of groundwater level data loggers in observation wells.

Finally, it is recommended that aggregate scale water use (licenced extraction) data for unconfined management zones of the LLCWAP are publicly available as this will allow for independent and full accounting of the water balance across the LLC. At present, independently assessing water use is not possible without such information.

5.4 Wetland management in plantations

The review works undertaken by this research have identified several key recommendations to improve wetland management in the LLC region, and many are applicable to any area of plantation forest where wetland features are present.

5.4.1 Review of key terms

Differences in the definition of wetland are relatively minor at the global, national and state level.

- It is suggested that the most relevant definition for the LLC region would be that provided by the South Australian *Landscape South Australia Act (2019)*. This definition has specific exclusions relevant to the LLC region, for example excluding dams and reservoirs. However it does not exclude drainage lines built for land reclamation. It is recommended that the status of drainage features which have evolved into, or influence, wetlands be clarified.

There is no reference to 'GDEs' in state legislation and regulation, nor is there a definition specific to the LLC region provided in regional policy documents such as the LLCWAP.

- It is recommended that there should be a specific definition in local policy documents as GDEs are an identified feature in many plans and policies. The methods used to determine what is, and is not, a GDE should be considered.

5.4.2 Techniques used to determine if a wetland is a GDE

There are several techniques applied in literature used to determine whether a wetland feature is also a GDE. In the LLC region, this is typically limited to proximity to groundwater.

- There is scope to consider the GDE status of wetlands using measures of (say) dry season wetness using satellite data, particularly for larger features.
- There appears to be little 'on ground' assessment of the GDE status of wetlands in the LLC region available in the public realm which can be used to verify the findings of the current broadscale assessment methods from desktop assessments. It is recommended that where such data exists for individual wetlands by land managers, it is made available to other stakeholders for further verification of existing broadscale techniques.
- Further recommendations relating to wetland management were provided to authorities by an independent review of science by the Goyder Institute for Water Research which are still relevant. They included:
    - Additional groundwater monitoring wells in key areas of concern
    - Further use of remote sensing methods for monitoring long term change in wetlands and GDEs
    - Collection of further hydrogeological data including aquifer transmissivity, groundwater surface water interactions and recharge characteristics near wetlands and GDEs

    - Collecting ecological data from wetlands and other GDEs, especially those of high/very high value, over a longer time period
    - Development of a monitoring program to collect data including field measurements, and remotely sensed Normalized Difference Vegetation Index to assess changes in distribution and groundwater dependency of remnant patches of vegetation GDEs
- Ultimately, some consideration of the 14,373 features listed in the LLC prescribed wells area is considered necessary to determine which of the wetland features in the LLC region currently exist and need management, which do not exist and may be restored and which have never or currently do not exist in any meaningful way.

5.4.3 Wetland condition and valuation assessment techniques in the LLC

Review of data and communication with project partners indicated that there are several wetland condition assessment techniques being applied in the region by forest managers and local authorities.

- Due to the limited resources for assessing and prioritising efforts to manage and restore wetlands, it is recommended that one technique suitable for condition and value assessment commonly be applied in the LLC region.
- Where condition assessment alone is inadequate for a value assessment, condition assessment should be applied in a manner such that it may at least inform value assessment – for example, a condition assessment by a plantation manager may only partly satisfy the needs of a value assessment, but available data may allow for authorities to prioritise (or subsidise land managers) collecting additional details to enable a value assessment.

5.4.4 Prevalence and condition of wetlands in or near plantation forests in the LLC

There are 110 high or very high value wetlands near (in, or withing 200 m of) plantations and 3.902 where there is no or limited data to provide a value assessment. These wetlands may range from very high to low value features, and there may be formal assessment or knowledge that could be shared to clarify this.

- This further reinforces the recommendation that data collected by plantation managers and authorities be, where possible, useful for condition and value assessment, and shared. This could have strong benefits in reviewing the LLCWAP by reducing potential for high uncertainty in quantifying risk to ecosystems.
- It is recommended that if there is no recognisable wetland feature currently present, the presence of the feature in the wetland database should be reviewed, or marked as historical.

5.4.5 Justification and benefit of setbacks

The review of wetland buffer and setback requirements including Australian state regulation and codes of practice has found a variety of definitions and protection measures are in practice. There are varying definitions of what constitutes a wetland, but in general definitions are provided. There is however little guidance on what should occur in a setback area in national guidelines. There is also little information provided to link the specified requirements to protect wetlands with research and case studies which support their effectiveness.

- It is recommended that forest management guidelines provide more explicit guidance about what should occur in a setback area – for example, advice on how a setback should be vegetated (if at all), and what management practices should be in place to prevent weed growth.

- There is little data presented to support existing setback distances It is recommended that authorities and industry consider research comparing the impacts of different setbacks on wetland condition over time. Any existing studies that have informed guidelines should be provided to support recommendations.

5.4.6 Presence of protected wetlands in the LLC region

The plantations in the LLC region are situated in a region near three Ramsar listed wetland areas of global significance and 11 wetland areas of national importance. DEW have indicated that many wetlands remain to be recognised so this number may increase. There are also currently 401 wetland features of high or very high value which have management requirements as per the LLCWAP, 134 being listed since the current LLCWAP was implemented, with some concern over limited sharing of this increase in sites was noted by forest managers.

- It is recommended that forest managers ensure that up to date records of high and very high value wetland locations are maintained and seek information from DEW and LCLB about what features may soon be acquiring high or very high value status, or those that may soon be listed as wetlands of national or international importance. The latter two categories have much larger setbacks and as such it is vital to understand what sites may soon be listed nationally or internationally important to ensure that decision making about new plantation areas, or replanting areas, consider management implications.
- It is recommended that DEW and/or the LCLB should actively inform landowners of the existence of high and very high value wetland and other GDE features on their land.

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