

# Goyder South East Project

## A new approach for modelling groundwater recharge in the South East of South Australia using MODFLOW

Rebecca Doble<sup>1</sup>, Trevor Pickett<sup>2</sup>, Russell Crosbie<sup>1</sup>, Leanne Morgan<sup>3</sup>

<sup>1</sup>CSIRO Land and Water Flagship, Adelaide

<sup>2</sup>CSIRO Land and Water Flagship, Brisbane

<sup>3</sup> Flinders University of South Australia, Adelaide



Goyder Institute for Water Research  
Technical Report Series No. 15/26



[www.goyderinstitute.org](http://www.goyderinstitute.org)



**Goyder Institute for Water Research Technical Report Series ISSN: 1839-2725**

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Water, CSIRO, Flinders University, the University of Adelaide and the University of South Australia. The Institute will enhance the South Australian Government's capacity to develop and deliver science-based policy solutions in water management. It brings together the best scientists and researchers across Australia to provide expert and independent scientific advice to inform good government water policy and identify future threats and opportunities to water security.

Enquires should be addressed to:



The following associate organisation contributed to the report:



Goyder Institute for Water Research  
Level 4, 33 King William Street  
Adelaide, SA, 5000

tel: 08-82365200  
e-mail: [enquiries@goyderinstitute.org](mailto:enquiries@goyderinstitute.org)

**Citation**

Doble, R.C, Pickett, T., Crosbie, R.S., Morgan, L., 2015, *A new approach for modelling groundwater recharge in the South East of South Australia using MODFLOW*, Goyder Institute for Water Research Technical Report 15/26

**Copyright**

© 2015 CSIRO To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of CSIRO.

**Disclaimer**

The Participants advise that the information contained in this publication comprises general statements based on scientific research and does not warrant or represent the completeness of any information or material in this publication.

# Contents

Acknowledgments .....	v
Executive summary .....	vi
Recharge estimation .....	vii
A new MODFLOW net recharge package (NETR).....	vii
Estimating recharge for the regional model .....	ix
Future work.....	xii
1 Introduction .....	1
2 Methods .....	3
2.1 Site description .....	3
2.2 Conceptualisation .....	4
2.3 MODFLOW model development.....	4
2.4 WAVES modelling .....	6
2.5 Landscape key and net recharge lookup table development.....	19
2.6 MODFLOW modification.....	20
2.7 Model testing.....	20
3 Results .....	21
3.1 WAVES outputs.....	21
3.2 Testing net recharge with a static water table .....	24
3.3 Modifying the MODFLOW model .....	30
3.4 Outputs from the South East model.....	31
4 Discussion.....	35
5 Conclusions .....	38
References .....	39
Appendix A MODFLOW NRF package .....	42
Appendix B MODFLOW lookup table.....	46
Appendix C Code for processing WAVES outputs.....	49
Appendix D Depth to water table vs net recharge curves .....	87

# Figures

Figure 1 Example groundwater depth vs. net recharge curves generated from WAVES modelling for (a) Mount Gambier Softwoods on Soil type 2, (b) Bordertown crops on soil type 5, (c) Lucindale perennial grazing on soil type 5 and (d) Lucindale Native vegetation on soil type 2. Net recharge is indicated by the black line. Other unsaturated zone fluxes used to calculate net recharge are also shown: transpiration (OS_T, red), canopy interception (OS_i, orange), soil evaporation (Soil_E, yellow), runoff (Q, green), gross recharge (Gross_R, light blue) and ET from groundwater (ETGW, purple). ....	viii
Figure 2. Conceptual diagram of the modelling process with the new net recharge MODFLOW package (NETR). ....	x
Figure 3. Comparison of the mean annual net recharge from the remote sensing derived water balance (left) and the look-up table approach (right) .....	xii
Figure 4 The Lower Limestone Coast Prescribed Wells Area, showing elevation and regional geology. ....	3
Figure 5 Conceptualisation of the modelling process .....	5
Figure 6. Mean annual rainfall across the region also showing selected climate stations for 1-D recharge modelling. ....	8
Figure 7. Thiessen polygons developed from the climate stations, used to develop the landscape key. ...	9
Figure 8. Soil clay content as classified into 7 classes based upon data from ASRIS (Johnston et al. 2003). Note the discontinuity at the SA/Victorian border due to different definition of soil types. ....	11
Figure 9. Land use classes from ACLUMP mapping used in the modelling based upon reclassifying data from (ABARE-BRS 2010). ....	13
Figure 10. Average annual depth to water table (DTWT) for the years 2001 to 2010, kriged groundwater elevation measurements subtracted from a ground surface DEM. Note that the data does not completely cover the eastern extent of the model domain. ....	17
Figure 11. Average depth to water table (DTWT) for 2008 (Morgan et al. 2015): kriged groundwater elevation measurements subtracted from a ground surface DEM. ....	18
Figure 12 Development of the landscape key, with (a) climate, (b) vegetation and (c) soil information, resulting in (d) unique identifier codes. ....	19
Figure 13 Example depth vs. flux curves generated from WAVES modelling for Mount Gambier native vegetation on Soil type 5, showing overstory transpiration from both soil and groundwater (OS_T), overstory interception (OS_i), evaporation from the unsaturated zone (Soil_E), runoff (Q), gross recharge (Gross_R), evapotranspiration directly from groundwater (STGW) and net recharge (net_R). .	21
Figure 14 Example groundwater depth vs. net recharge curves generated from WAVES modelling for (a) Mount Gambier Softwoods on Soil type 2, (b) Bordertown crops on soil type 5, (c) Lucindale perennial grazing on soil type 5 and (d) Lucindale Native vegetation on soil type 2. Net recharge is indicated by the black line. Other unsaturated zone fluxes used to calculate net recharge are also shown: transpiration (OS_T, red), canopy interception (OS_i, orange), soil evaporation (Soil_E, yellow), runoff (Q, green), gross recharge (Gross_R, light blue) and ET from groundwater (ETGW, purple). ....	23
Figure 15 Mean annual net recharge from WAVES modelling using composite 2001 – 2010 DTWT data. Mean is 14.7 mm/yr. ....	25
Figure 16 Mean net recharge from water balance analysis of MODIS satellite data using CMRSET algorithms, composite 2001 - 2010. Mean is 40 mm/yr (adjusted to not include the eastern strip not modelled in Figure 15. ....	26
Figure 17 Mean annual net recharge from WAVES modelling using the 2008 average static watertable. Mean is 43.5 mm/yr .....	27

Figure 18 Mean annual net recharge from WAVES modelling using the 2008 average static watertable and updated vegetation parameters. Mean is 20.8 mm/yr .....	28
Figure 19 Mean net recharge from water balance analysis of MODIS satellite data using CMRSET algorithms, 2008. Mean is -36.6 mm/yr .....	29
Figure 20 The test model used to confirm performance of the new MODFLOW Net Recharge (NRF) package.....	30
Figure 21 Groundwater head output from the layer 1 of the WAVES-MODFLOW model using the net recharge lookup function. ....	32
Figure 22 Groundwater head output from the layer 1 of the regional South-East model from Morgan et al. (2015).....	33
Figure 23 Groundwater flux vs. DTGW curves for transpiration of riparian vegetation in Arizona, (Baird and Maddock III 2005; Baird et al. 2005), evaporation from a fine sandy loam, California (Talsma 1963), recharge to a sandy aquifer in the Tomago Sandbeds, NSW, Australia (Crosbie 2003) and an example of net recharge from this report (multiplied by 10 for clarity).....	37

## Tables

Table 1 Parameters used in the MODFLOW model .....	6
Table 2 Climate zones used in the WAVES modelling. Average annual rainfall is from 1889 to 2013 as recorded by SILO (Jeffrey et al. 2001) and the average annual PET is FAO56 (Smith et al. 1992) from 1889 to 2013 as recorded by SILO (Jeffrey et al. 2001).....	7
Table 3 Soil types and parameters used in the WAVES modelling (Carsel and Parrish 1988) .....	11
Table 4 Land use types used in the WAVES modelling.....	14
Table 5 Vegetation parameters used in the WAVES modelling .....	15
Table 6 Water budget for the South East comparing results from the modified WAVES-MODFLOW model and regional South-East MODFLOW model from Morgan et al. (2015). .....	31

# Acknowledgments

This work was funded by the Goyder Institute for Water Research through the South East Regional Water Balance Project.

Thanks to the following people for acting on the Technical Working Group for that project and providing useful feedback on various technical aspects:

Okke Batelaan (Flinders University)

Dirk Mallants (CSIRO)

Glen Walker (formerly CSIRO)

Graham Green (DEWNR)

Saad Mustafa (DEWNR)

Jeff Lawson (DEWNR)

Chris Li (DEWNR)

Cameron Wood (DEWNR)

Saad Mustafa (DEWNR)

# Preface

## South East Regional Water Balance Project Background

The South East Regional Water Balance project is a collaboration between Flinders University, CSIRO and the Department of Environment, Water and Natural Resources (DEWNR), funded by the Goyder Institute for Water Research. The project commenced in September 2012, with the objective of developing a regional water balance model for the Lower Limestone Coast Prescribed Wells Area (LLC PWA). The project was initiated following conclusions from the South East Water Science Review (2011) that, due to a number of gaps in understanding of processes that affect the regional water balance, there is uncertainty about the amount of water that can be extracted sustainably from the Lower Limestone Coast region as a whole. The review also concluded that, because of the close link between groundwater and surface water resources in the region, surface water resources and ecosystems are particularly vulnerable to groundwater exploitation.

The South East Regional Water Balance project follows on from the report of (Harrington et al. 2011), which recommended that a consistent framework of models is required to support water management in the South East, with the first step being a regional groundwater flow model to:

- bring together all existing knowledge,
- address regional scale water balance questions
- provide boundary conditions for smaller scale models to address local scale questions, including those around “hotspot” areas and significant wetlands.

(Harrington et al. 2011) also identified the critical knowledge gaps that limit the outcomes from a regional scale model. These included but were not limited to:

- Spatial and temporal variability in groundwater recharge and evapotranspiration.
- Interaquifer leakage and the influence of faults on groundwater flow.
- The nature of wetland-groundwater interactions
- Understanding of processes occurring at the coastal boundary
- Surface water-groundwater interactions around the man-made drainage network
- The absence of information on historical land use and groundwater extraction

The South East Regional Water Balance project has included numerous tasks that have sought to improve the conceptualisation of the regional water balance, address some of the critical knowledge gaps, incorporate this and existing information into a regional groundwater flow model and understand how this improved understanding can be used in the management of wetland water levels.



# Executive summary

## Recharge estimation

This study builds upon decades of recharge estimation in the South East to provide the first spatially continuous estimation of recharge in the region that can be included in a groundwater model. Phase 1 of the Goyder recharge project undertook ground-truthing of net recharge estimates derived from remotely sensed MODIS/CMRSET evapotranspiration used in a water balance on an eight-day timestep and a ~ 250 m grid (Crosbie and Davies 2013; Crosbie et al. 2015). The remotely sensed net recharge estimates were ground-truthed against hundreds of point scale water table fluctuation estimates of recharge over the period 2001-2010. A further comparison against the hundreds of previous point scale estimates of recharge demonstrated that the new CMRSET derived net recharge estimates were not biased overall, but there were considerable differences between the CMRSET and field data at individual points. CMRSET estimates of net recharge ranged from over 200 mm/yr (net recharge) to -200 mm/yr (net evapotranspiration). In order to perform a regional-scale comparison with other methods of recharge estimation, an average was taken over the whole study area for the 10 year period 2001-2010. This overall net recharge was 40 mm/yr. While this is a useful comparison for validation purposes, this is a very broad-scale average, and recharge ranges over several orders of magnitude across the study region. Resource allocation decisions may require recharge estimates on a more local scale.

As well as the expected dependence of recharge upon climate, soil type and vegetation type, it was also found that gross recharge under all vegetation types was strongly dependent upon depth to water table (DTWT) for groundwater depths up to 6 m. The net recharge estimates had a different relationship with DTWT as this also incorporates evaporation and transpiration processes that are known to exhibit this relationship.

Phase 2 of the project, described in this report, aimed to test the validity of the observations of the depth dependence of recharge and apply them to the South East regional MODFLOW model. A numerical experiment was performed using the SVAT model WAVES. Using the same soil, vegetation and climate inputs the model was run over 100 years for various depths to water table to investigate these relationships. The relationships seen between soil evaporation and transpiration and depth to water table were found to be consistent with those described in the literature and the relationships between both gross and net recharge found in the Phase 1 study were replicated in this modelling (Figure 1).

The relationships that were observed between both gross and net recharge and depth to water table are often not explicitly reported in the literature, despite evidence of them in a number of papers, therefore little thought has been put into how to model them in a regional groundwater model. This will be addressed in this report.

The aim of the study was to develop a methodology for modelling recharge that could be incorporated into the regional MODFLOW groundwater model developed in Morgan et al. (2015). Due to the parallel development of the recharge estimation method and the MODFLOW model, a full calibration of the two processes was not possible. As such, the recharge under native vegetation and forestry in this report has been found to be higher than previously measured, and should not be used for water allocation purposes until calibration of the MODFLOW-WAVES model has taken place. Several sources of data on vegetation water use are presented in the text.

## A new MODFLOW net recharge package (NETR)

Conventionally in MODFLOW, recharge is applied as a single, time-varying parameter for each model cell that is independent of the depth to water table (RCH package). This approach is suited to regional where

the water table is well below the land surface. The evapotranspiration functionality in MODFLOW was originally developed to mimic evaporation from soil alone (Talsma 1963). The EVT or ETS packages facilitate a linear relationship between ET and depth to water table, with the evapotranspiration being at a maximum when the water table is at the land surface and then decreasing to zero at the extinction depth. These existing packages are not suited for simulation of observations in the South East, where gross recharge is dependent on depth to water table and the evapotranspiration is not at a maximum when the water table is at the surface.

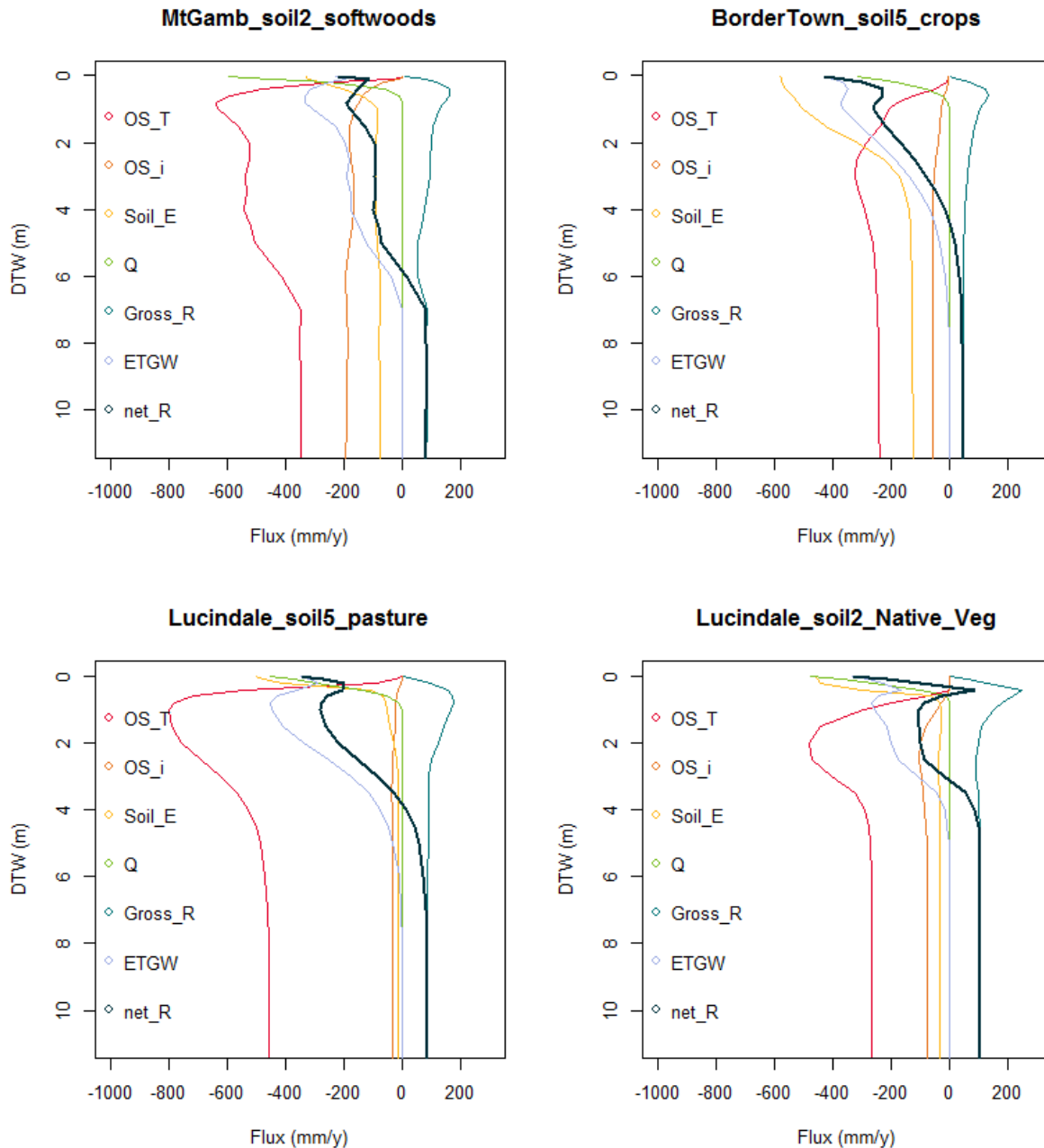


Figure 1 Example groundwater depth vs. net recharge curves generated from WAVES modelling for (a) Mount Gambier Softwoods on Soil type 2, (b) Bordertown crops on soil type 5, (c) Lucindale perennial grazing on soil type 5 and (d) Lucindale Native vegetation on soil type 2. Net recharge is indicated by the black line. Other unsaturated zone fluxes used to calculate net recharge are also shown: transpiration (OS\_T, red), canopy interception (OS\_i, orange), soil evaporation (Soil\_E, yellow), runoff (Q, green), gross recharge (Gross\_R, light blue) and ET from groundwater (ETGW, purple). Note that transpiration rates were found to be higher than those measured in previous field studies

Recent MODFLOW packages have been developed to better represent ET and recharge functions, such as the RIP-ET (Maddock and Baird 2002), UZF (Niswonger et al. 2006) and Farm Process (Schmid et al. 2006). While these processes improve the conceptualisation of recharge and evapotranspiration, they may not be flexible enough to be applied in every modeling situation. The RIP-ET package is specifically designed for riparian vegetation and does not have the functionality to be applied to other vegetation in shallow groundwater areas. The UZF and Farm Process packages are highly complex, significantly increasing computational effort and again have limited flexibility with vegetation input parameters.

To enable these processes as observed to be replicated in the regional groundwater model, a more complex coupled unsaturated-saturated zone model would normally be required rather than the relatively simple MODFLOW RCH, EVT or ETS packages. Coupled unsaturated-saturated models generally need a much finer numerical discretisation leading to run times that can be orders of magnitude greater than an equivalent MODFLOW model. Consequently these complex model codes are generally only used in a small scale research models rather than regional scale management models. One of the aims of this regional scale model of the South East is to investigate the predictive uncertainty in elements of the water balance. This requires running the model hundreds of times at a minimum with varying parameter combinations which poses strong constraints on model stability, making the more complex codes impractical. The solution pursued here was to create a new MODFLOW package that can incorporate the depth dependant net recharge that was observed in Phase 1.

The existing segmented evapotranspiration (ETS) package returns an ET rate dependant on the depth to water table from a piecewise linear function that is limited to having the maximum when the water table is at the surface decreasing to zero when the water table reaches the extinction depth. The new MODFLOW net recharge package (NETR) relaxes these restrictions to enable the piecewise linear function to be both positive and negative, to have the maximum at any depth and not be restricted to having a flux of zero at the maximum depth. The package reads a landscape key that is assigned to each grid cell and then reads the values of the piecewise linear function from a look-up table that has a row for each landscape key value and interpolates according to the exact depth to ground water (Figure 2). The NRF package can use a new look-up table and landscape key for each stress period or continue to use the same inputs as the previous time step, this enables both transient land use and transient net recharge relationships to be incorporated into the model.

The new net recharge MODFLOW package (NETR) was tested on a small tutorial model of 17 x 17 cells and five layers to mimic the conventional RCH and EVT package behaviour. When the test model had recharge (RCH) only, the new package returned identical outputs for both water balance and heads. When it had evapotranspiration (EVT) only, the new package returned identical outputs for both water balance and heads. When both recharge (RCH) and evapotranspiration (EVT) were implemented, the new model returned net recharge outputs that were fractionally higher (but insignificant) than the combined output of the RCH and EVT packages, the difference is believed to be due to the sequencing of packages in MODFLOW. This confirmed that the functions were implemented into MODFLOW successfully.

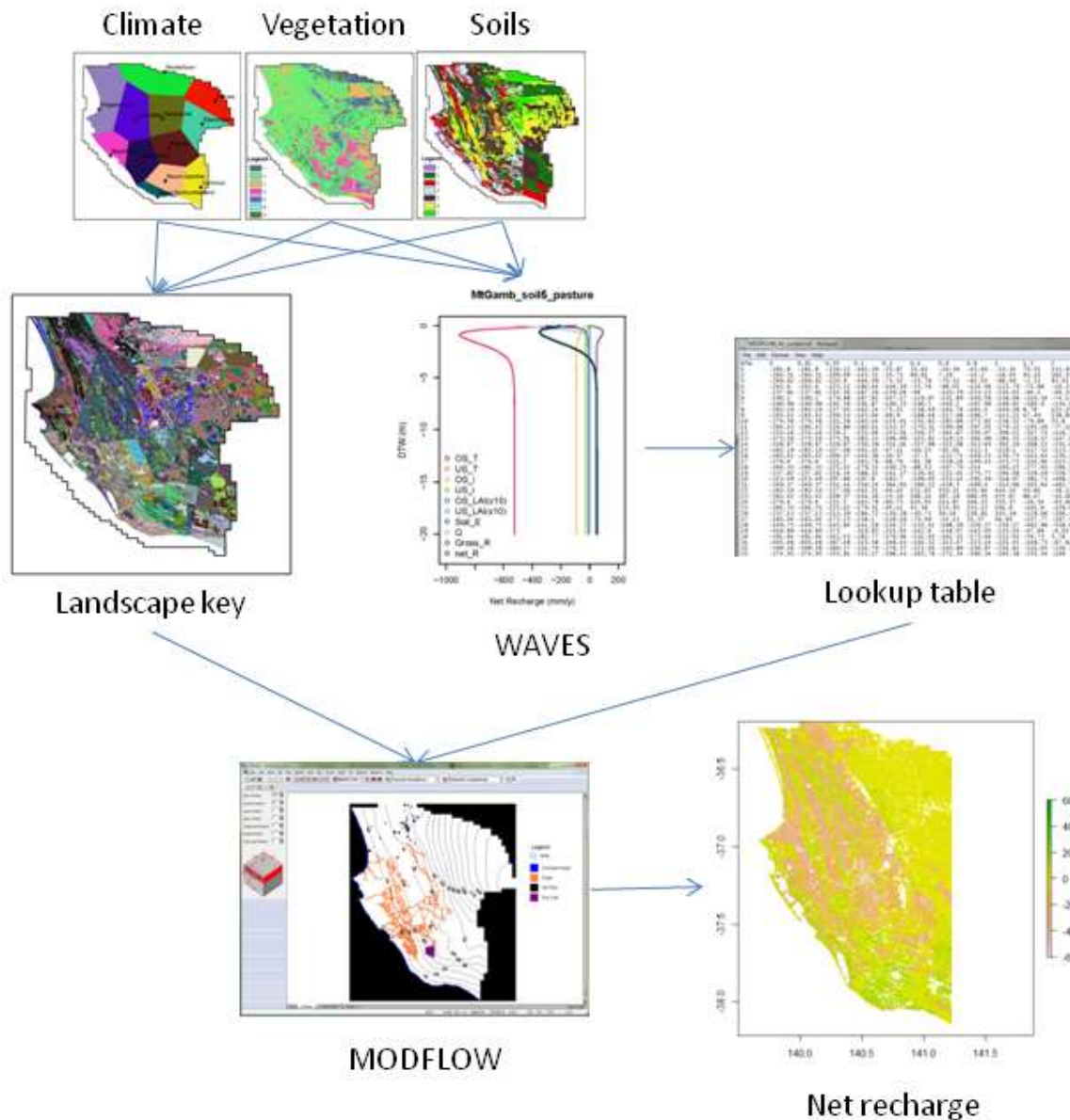
As a proof of concept, the test model demonstrated that the new net recharge package (NETR) works for both steady state and transient model instances but a more complex test in the regional model was necessary.

## Estimating recharge for the regional model

To test the new net recharge package more extensively it was incorporated into a transient version of the regional groundwater model, but run for ten years with the same parameters to replicate steady state. This was necessary for model convergence. The inputs needed were the landscape key and the look-up table.

The landscape key was developed based upon the factors found to be important determinants for net recharge. These were climate, soil type and vegetation type. The climate within the model domain was attributed based upon Theissen polygons around 12 representative climate stations. A discrete subdivision of the study site was required as the WAVES model would be run for each of the climate zones. The soil type was attributed according to the average clay content of the top 2 m of the soil profile estimated using

the ASRIS database, this was split into seven classes. The vegetation type was a simplification of ACLUMP (Australian Collaborative Land Use and Management Program) mapping (ABARE-BRS 2010) down to eight functional classes that behave differently for recharge. This gave a potential for 672 individual classes in the landscape key of which currently 502 physically exist in the region.



**Figure 2. Conceptual diagram of the modelling process with the new net recharge MODFLOW package (NETR).**

The look-up table was populated using the WAVES model. Despite the fact that only 502 currently exist, all 672 landscape classes were modelled using WAVES to support possible future scenario modelling. For each of the 672 landscape classes, WAVES was run for 26 depths to water table ranging from 0.01 m to 20 m. The net recharge was then averaged over 100 years to give a long term steady state net recharge for populating the look-up table.

The approach was algorithmically tested using R with a static water table derived from averaged spring and autumn water levels and a 2008 water table. This algorithmic test returned a net recharge value for every grid cell in the raster using the static water table, landscape key and look-up table. This test provided a raster of net recharge that should be able to be compared with the net recharge raster derived from the remotely-sensed ET. This test demonstrated that the logic of the look-up table approach worked successfully but the values in the look-up table were not correct. The resulting net recharge raster was too extreme, the inter-dunal flats had a negative net recharge (groundwater discharge) that was much greater

in magnitude than that estimated through the water balance and also the dunes had much greater positive net recharge than that estimated through the water balance. The model did represent the spatial distributions of recharge in bluegum forestry areas south of Lucindale and the pine plantations around Penola well compared with the MODIS/CMRSET data, but the magnitude of net recharge should be further assessed against local studies. Irrigated areas were shown to be recharging in the WAVES outputs due to the additional irrigation volume applied, while the MODIS/CMRSET data indicated that these areas were evaporating as applied irrigation was not included in the water balance. Overall the look-up table approach had an areal average net recharge rate of 15 mm/yr whereas the remote-sensing derived water balance had an areal average net recharge rate of 40 mm/yr (Figure 3).

The final test of the new net recharge MODFLOW package (NETR) was incorporating it into the regional groundwater model. The model was run for ten years in transient mode using steady state parameters to mimic steady state conditions. This was to match the conditions of the regional steady state model, which did not have ET as a function of DTWT, and therefore converged more easily. The modified MODFLOW model converged successfully demonstrating that the new package works.

The resulting water table was lower than the regional South East model described in the regional modelling report (Morgan et al. 2015) and with a flatter piezometric surface in the lowlying areas of the model and a steeper water table in the highland area. The water balance was somewhat different from the results from the different recharge approach in Task 1, with lower overall net recharge (both positive and negative ET), lower inflows and outflows through constant head boundaries and approximately 50% of the drain discharge. Forested areas were better represented than other vegetation types, while higher elevations were better represented than those with extremely shallow groundwater (DTWT <1m). Areas for improvement include better calibrated vegetation parameters in the WAVES model and improvements in the representation of the evaporation surface in the large cells of the MODFLOW model, perhaps using probabilistic methods. These improvements will be important for producing and using the look-up table, which will affect the results by reducing the amount of under or over estimation of the recharge value. The various water balance components have not yet been tested against field measurements, and further work is required to do so.



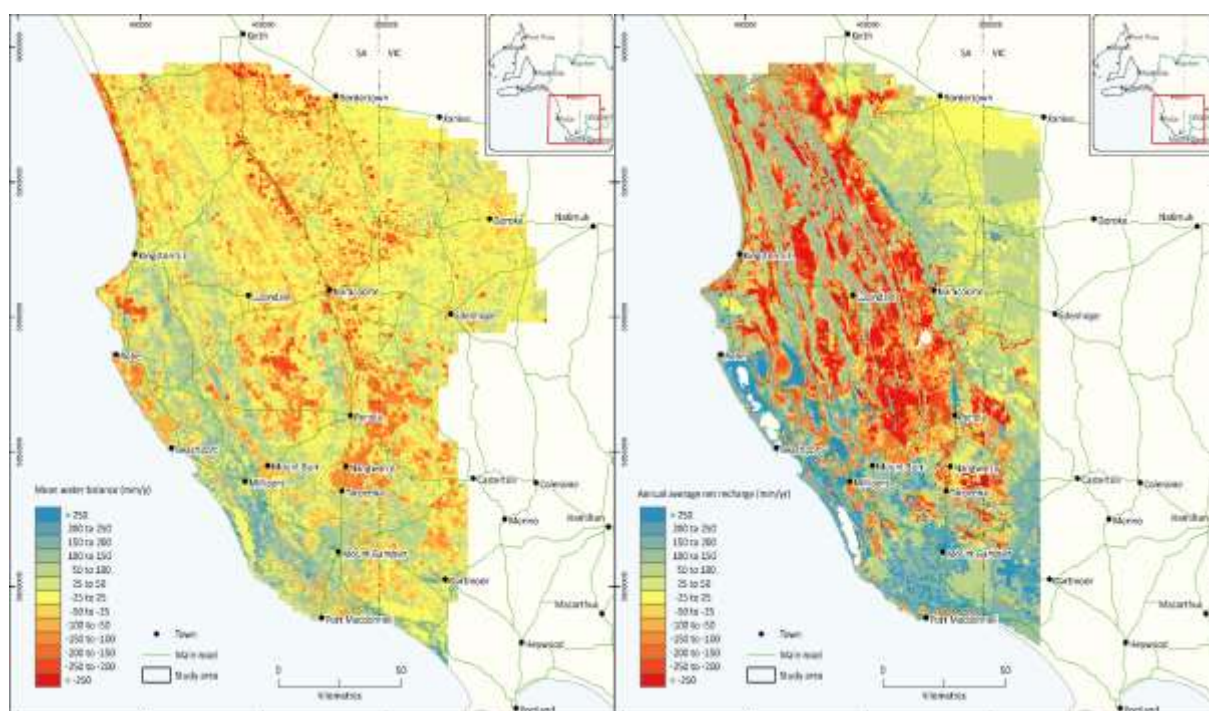


Figure 3. Comparison of the mean annual net recharge from the remote sensing derived water balance (left) and the look-up table approach (right)

## Future work

The unsaturated zone modelling (WAVES) is not currently capturing the magnitude of the recharge when compared to the remote-sensing derived water balance estimates of recharge, as shown in Figure 3. The source of this discrepancy needs to be investigated and rectified. This should be done in parallel with an analysis of the CMRSET water balance estimate of recharge to determine assess the proportional accuracy of both methods.

The WAVES modelling was only very loosely calibrated and would benefit from a formal automated calibration. This could be done by coupling WAVES and MODFLOW with some of the R code that has already been developed. Alternatively, it could be done more simply by converting the net recharge curves into simple two or three parameter functions and writing code to translate these functions into a MODFLOW input file format.

The look-up table has only been implemented in a steady-state version of the regional groundwater model, transient testing is needed. This would require partitioning the input data into seasonal or historical net recharge estimations and comparing with equivalent CMRSET water balance approximations.

Uncertainty analyses to estimate parameter sensitivity and the impacts of different management and climate scenarios on aquifer sustainability are the ultimate goal of the modelling. This would provide a significant benefit to natural resource managers in the South East.

# 1 Introduction

Understanding groundwater sustainability relies on a confident approximation of aquifer recharge. Field estimations will provide a quantitative assessment of recharge at a point scale. These, however, are generally too sparse to provide information about the spatial distribution of recharge and evapotranspiration across a regional aquifer system. Some methods of estimating groundwater recharge, such as the chloride mass balance method (Allison and Hughes 1978; Scanlon 1991; Phillips 1994; Crosbie and Davies 2013; Crosbie et al. 2015) are historically cumulative, rather than providing estimations of current recharge volumes. The water table fluctuation method can predict gross recharge at a point scale, but requires additional estimates of ET to predict net recharge. Recharge at a spatial scale can also be estimated from remotely sensed ET data using a water balance method for individual points in time (Crosbie and Davies 2013; Crosbie et al. 2015). Although this data is associated with high uncertainty, it may provide a better understanding of how recharge and ET function at a regional scale.

To answer questions about how management practices or climate change affects groundwater recharge and resource sustainability, numerical modelling is required. The conventional groundwater-modelling tool, MODFLOW, allows evapotranspiration to be represented as either a simple depth dependent function; EVT (Harbaugh 2005) or a segmented linear depth dependent function; ETS (Banta 2000), which has strict requirements for ETS at the surface to be the maximum rate of ET, and ETS below the extinction depth to be zero. Recharge is represented separately as a single value per cell per stress period; RCH (Harbaugh 2005). The Goyder SE Phase 1 report indicated that net recharge to groundwater was more complex than these representations, and in some cases was dependent on depth to water table (DTWT) (Crosbie and Davies 2013; Crosbie et al. 2015).

While evapotranspiration is known to be controlled by depth to groundwater (Gardner and Fireman 1958; Talsma 1963; Baird and Maddock III 2005; Doble et al. 2006), many studies show that recharge can also be depth dependent where shallow groundwater is present (Sophocleous 1992; Crosbie 2003). Recharge and evapotranspiration processes are often combined as net recharge (recharge minus ET from groundwater) to compare with field measures of recharge including chloride mass balance (Anderson 1945; Wood 1999; Crosbie et al. 2015) and satellite based water balance methods (Szilagyi et al. 2013). With increasing use of remote sensing data, the use of net recharge as a representation of recharge and groundwater ET is becoming more common.

Regional scale recharge and ET data from remote sensing is improving our understanding of these processes at a regional scale. At the same time, uncertainty analysis is another growth area of hydrogeology that is vital for developing scientifically credible models intended for groundwater management. Uncertainty analyses give an indication of model sensitivities and provide insight into the confidence or risk of certain management outcomes. They can require many hundreds of model runs, and therefore rely on models that are robust, converge easily and have rapid computational times.

Providing a credible, robust groundwater model for the South East therefore requires a more detailed approximation of recharge and evapotranspiration processes within the constraints of a realistic computational duration. There were three options for the region: using standard MODFLOW representation of ET and recharge, using more complex representations of recharge and ET processes using models coupled with MODFLOW, and using more complex models to emulate behaviour of the recharge and ET functions, which are then used by MODFLOW.

The standard MODFLOW representations did not allow the net recharge – DTWT relationships under forestry that were developed in Phase 1 of the Goyder South East project through use of MODIS/CMRSET remote sensing data to be incorporated into the regional model.

Recharge and ET could have been modelled as groundwater depth dependent processes using unsaturated groundwater models such as HydroGeoSphere (Therrien et al. 2006; Brunner and Simmons 2011), HYDRUS (Šimůnek et al. 2011) or Mike-SHE, or MODFLOW additions such as the Farm Process (Schmid et al. 2006) or MODFLOW-UZF1 package (Niswonger et al. 2006). In practice, however, most large groundwater

management zones are modelled using simple saturated groundwater flow packages such as MODFLOW (Harbaugh 2005) due to the trade off between model conceptual complexity and the higher level of discretisation required to adequately represent the ground surface, and thus groundwater – surface water interactions. This is particularly important for uncertainty analysis.

Emulation of recharge and ET processes using a more complex vegetation/atmosphere/water model was selected as the most appropriate method for the South East. The relationships developed in this emulation process were aggregated into a lookup table referenced by a modified version of MODFLOW which could then be used for assessing management scenarios, including uncertainty analysis.

This report describes the proof of concept development of a method for emulating recharge and ET behavior in the shallow groundwater conditions. It describes the incorporation of the resulting net recharge – depth to water table (DTWT) relationship into a lookup table and new MODFLOW package (NETR) to use the lookup table to calculate net recharge based on the depth to water table in a cell. The method was applied to a steady state regional groundwater model developed for the South East region of South Australia and western Victoria, which is characterized by shallow underlying groundwater, groundwater dependent wetlands and constructed drains.



## 2 Methods

### 2.1 Site description

The study site was located in the south east of South Australia and western Victoria (Figure 4) and is part of the Otway and Murray Basins. The site comprises an area of 29,000 km<sup>2</sup> and covers the extent of the Dilwyn Formation, a tertiary confined sand aquifer. The Dilwyn Formation is overlain by the unconfined Quaternary/upper-mid Tertiary Gambier/Murray Group limestone aquifer. These aquifers are separated by an upper-mid Tertiary aquitard. The region slopes gently away from the highest elevation in the north-east toward the south-west coast. There is a break of slope along the Kanawinka fault (Figure 4) and some undulation in the lowlying south-west of the region due to dune/flat systems produced by Pleistocene marine transgressions.

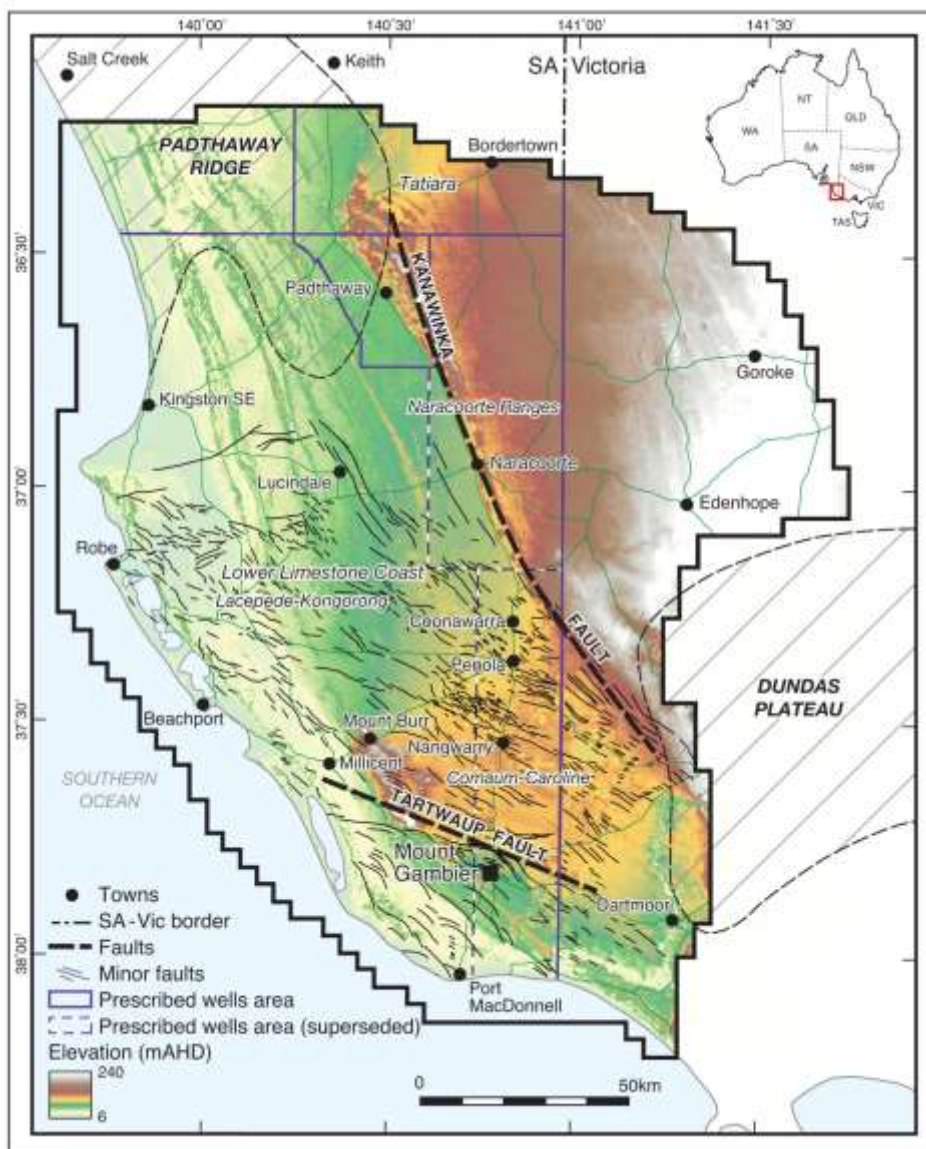


Figure 4 The Lower Limestone Coast Prescribed Wells Area, showing elevation and regional geology.

The south west of the region has relatively shallow groundwater underlying the sandy dune system, while the north east has a deeper water table. There are numerous wetlands within the study site and some low lying areas affected by salinisation.

The climate is Mediterranean, with winter dominant rainfall and hot dry summers. Land uses include grazing, annual cropping, remnant native vegetation and forestry. Irrigation of vineyards (west of the Kanawinka fault) and pasture (generally) also occurs. Forestry species are dominated by *Pinus radiata* and *Eucalyptus globulus* (Tasmanian Blue Gum). A more detailed site description is provided in the Phase 1 report.

## 2.2 Conceptualisation

MODFLOW 2000 was used to develop a groundwater flow model for the region (Harbaugh et al. 2000; Morgan et al. 2015). Recharge and evapotranspiration was modelled with more detail using the integrated water and energy model, WAVES (Zhang and Dawes 1998b; Dawes et al. 2004). Functions of net recharge (recharge minus ET from groundwater) vs. groundwater depth were developed from over 17 000 WAVES model runs, for twelve climate zones, seven soil types, eight vegetation types and 26 depths to groundwater.

Each cell of the MODFLOW model was represented by a landscape key, which was a combination of climate zone, soil type and vegetation type developed from maps of land use, soil characteristics and proximity to meteorological stations (Figure 5).

The MODFLOW 2000 ETS package was modified to obtain net recharge from a look up table constructed from the net recharge – depth curves. Net recharge was calculated using the depth to groundwater and based on the landscape key associated with the cell. The net recharge was used to calculate the groundwater elevation for the next iteration and recorded in the water balance of the MODFLOW .lst file.

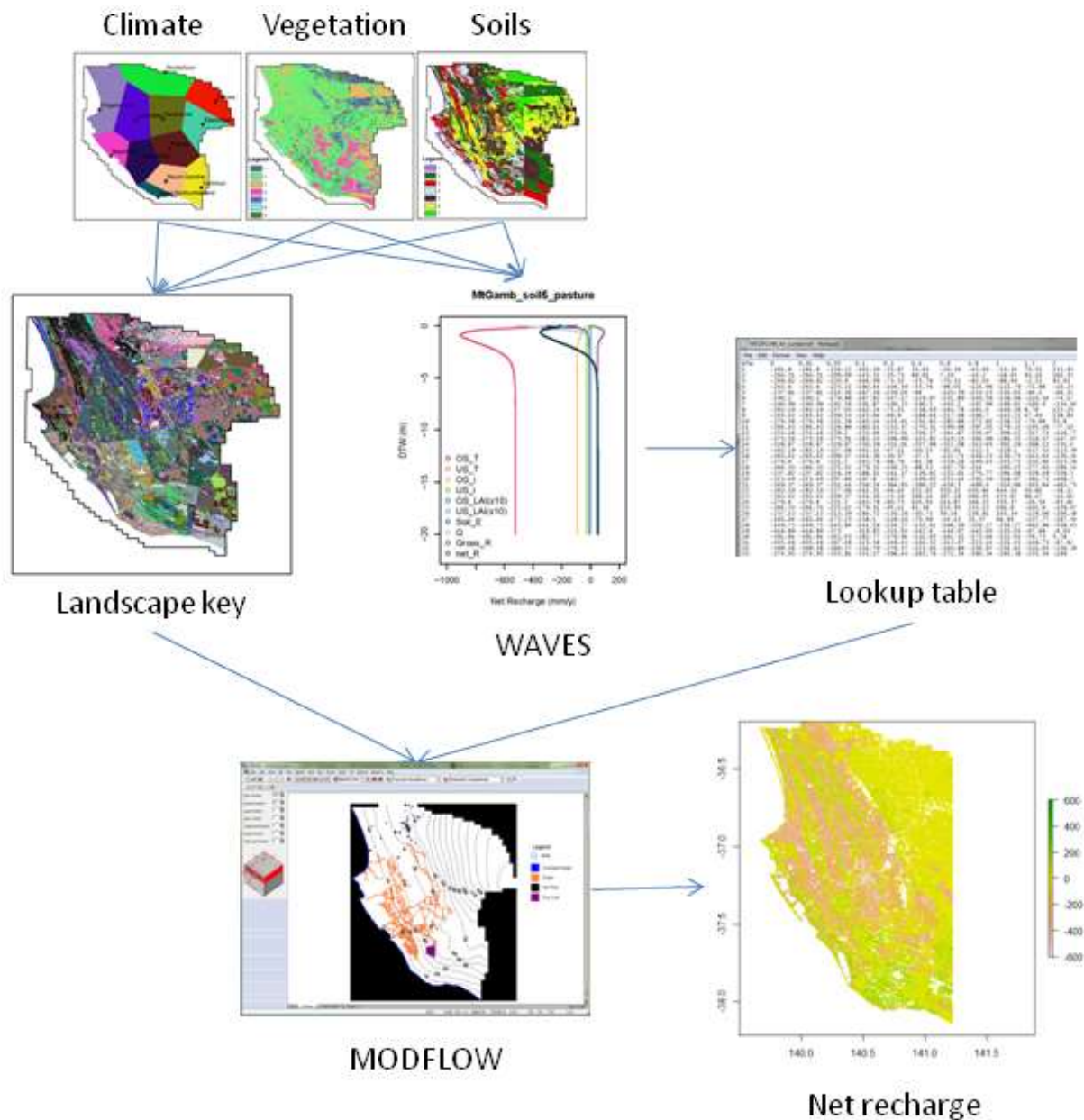
This methodology may be used for steady state model runs, using annual average rates of net recharge, for seasonal variations, using four stress periods and lookup tables per year of model runs, or for historical or synthetically constructed climate sequences, with seasonal or monthly stress periods and lookup tables. Similarly land use may be changed during the model runs, by updating the landscape key to represent, for example, forestry management – harvesting and planting, or irrigation development.

## 2.3 MODFLOW model development

The regional groundwater model is the first to span the Lower South East (LSE) and include both the unconfined and confined aquifers. The model was developed in MODFLOW 2000, a three-dimensional finite-difference code developed by the U.S. Geological Survey (McDonald and Harbaugh 1988; Harbaugh et al. 2000). Groundwater Vistas Version 6.4 (GV; Environmental Simulation Systems, Inc.) was used for both pre- and post-processing of the MODFLOW model. GV was also used to generate the input files for the calibration software PEST (Doherty 2005). The MODFLOW model was developed in parallel to the net recharge (NETR) package, then adapted to incorporate the NRF package to test the package performance.

The model domain covers an area of 42,112 km<sup>2</sup>, 224 km north-south by 188 km east-west. The bounding coordinates of the model domain are (Easting, Northing; MGA Zone 54): 377,300 m, 5,770,000 m in the south-west and 565,300 m, 5,994,000 m in the north-east. The rectangular model grid is orientated north-south. The domain is divided into 188 columns, 224 rows and three layers, which, accounting for inactive cells that are outside of the study area and within the study domain representing areas of basement outcropping, incorporates 75,260 active finite-difference cells. All of the cells have a uniform dimension of 1000 x 1000 m in the horizontal plane.

Although both steady state and transient conditions were simulated (Morgan et al. 2015), at this stage only the steady state model was used. The steady state model was run for the period January 1965 to December 1974. The decadal average recharge and extraction values were applied within the steady state model.



**Figure 5 Conceptualisation of the modelling process**

MODFLOW's PCG2 solver was used with convergence criteria set to 0.01 m for the maximum absolute change in head (HCLOSE) and to 1 m<sup>3</sup>/d for the water budget residual (RCLSE). The maximum outer iterations was set to 500.

A mean DEM value was assigned as the top of layer 1 elevation within the MODFLOW model. A hydrostratigraphic model was provided by DEWNR, as detailed within Section 8.2 of the Phase 1 report of this project (Harrington and Lamontagne, 2014). The hydrostratigraphic model was used to define three layers for use in the MODFLOW model. These layers represent a lower tertiary confined aquifer system, an upper-mid tertiary aquitard and a quarternary/ upper mid-tertiary unconfined aquifer. All layers were represented as confined in MODFLOW due to non-convergence issues within the transient version of the model when layer 1 was set as unconfined.

The model adopts an equivalent porous medium approach. The spatial partitioning of aquifer parameters was carried out using uniform hydraulic conductivity and storage coefficient values in each layer. The automated model calibration procedure in PEST was used (Doherty, 2005). PEST automatically runs the

model repeatedly and modifies parameters to improve the match between model predictions and field observations. The calibrated parameter values in each layer are shown in Table 1.

**Table 1 Parameters used in the MODFLOW model**

LAYER	Formation	PARAMETER	VALUE
1	<i>Quaternary/upper-mid tertiary aquifer</i>	$K_h$ (m/d)	163
		$S_s$ (/m)	0.006
2	<i>Upper-mid tertiary aquitard</i>	$K_v$ (m/d)	0.0001
		$S_s$ (/m)	$10^{-6}$
3	<i>Lower tertiary confined aquifer</i>	$K_h$ (m/d)	3.1
		$S_s$ (/m)	$10^{-7}$

No flow boundary conditions were applied along the non-coastal boundaries. Potentiometric contours are generally perpendicular to these boundaries and therefore this is considered appropriate. Along the coast, a density corrected specified head boundary was used in layer 1 and layer 3. A no flow boundary was applied in layer 2 along the coast.

The majority of the drains in the lower South East were constructed prior to 1970, while drains in the upper South East were constructed between 1998 and 2010. Drains were implemented into the model at stress periods corresponding to the start of the drain construction year.

Metered extraction volumes from groundwater bores were not available for the South East prior to 2009. The average post-2009 extraction volume was used for extraction volumes prior to 2009. Extraction was assumed to commence in January of the year that the well was constructed. Seasonal extraction wells were assumed to extract the annual volumes between October and March during the irrigation period, with zero extraction between April and September. For the steady state model, the January 1965 to December 1974 decadal average extraction volume was used for bores that were constructed prior to 1975.

Please refer to Morgan et al. (2015) for further details of the groundwater model development and input data.

## 2.4 WAVES modelling

The look-up table needed to be populated with net recharge values for every combination of depth to water table, soil, vegetation and climate. This had to be more flexible than just the land-uses that currently occur to allow for the possibility of land-use change within the modelling timeframe. For this reason, a full factorial experimental design was chosen for the net recharge modelling consisting of:

- 12 climate stations to cover the region both geographically and climatologically
- 7 soils types based upon a classification of the clay content of the soil
- 8 land-use types
- 26 discrete depths to water table

The model code chosen for the estimation of net recharge was the WAVES model (Zhang and Dawes 1998a), a soil-vegetation-atmosphere transfer model using an atmospheric boundary condition at the top and a fixed head (water table depth) as the bottom boundary condition. The model solves Richard's

Equation (Richards 1931) for water flow through the unsaturated zone and uses the integrated rate methodology (Wu et al. 1994) for dynamic vegetation growth. This model has been well tested for replicating field measurements for recharge (Zhang et al. 1999a), vegetation growth (Zhang et al. 1999b) and water balance (Crosbie et al. 2008). It has also been used extensively for scenario modelling of land use change (Zhang et al. 1996; Zhang et al. 1999a; Zhang et al. 1999b; Dawes et al. 2002) and climate change (Crosbie et al. 2013b; Crosbie et al. 2013a).

### 2.4.1 CLIMATE

Twelve climate stations were chosen to cover the region both geographically and climatologically (Table 2, Figure 6). Although ideally WAVES could be run for every grid cell with gridded climate data, the run time for over 27 000 active surface cells for each vegetation, soil and depth combination would be prohibitive. These stations cover the rainfall gradient from less than 500 mm/yr at Bordertown to almost 800 mm/yr at Mt Burr. On an annual basis the average annual rainfall is less than the annual average PET making this region water limited. However, over the winter months rainfall exceeds PET in all parts of the study area. The climate inputs required by WAVES are the daily rainfall, minimum and maximum temperature, the vapour pressure deficit and the solar radiation. This information was obtained from SILO (Jeffrey et al. 2001) for all climate stations.

**Table 2 Climate zones used in the WAVES modelling. Average annual rainfall is from 1889 to 2013 as recorded by SILO (Jeffrey et al. 2001) and the average annual PET is FAO56 (Smith et al. 1992) from 1889 to 2013 as recorded by SILO (Jeffrey et al. 2001).**

NAME	ZONE	LATITUDE	Longitude	Average rainfall (mm/yr)	Average PET (mm/yr)
Beachport	1	-37.480	140.013	698	944
Bordertown	2	-36.308	140.772	480	1160
Cape Northumberland (Port McDonnell)	3	-38.055	140.670	708	891
Dartmoor	4	-37.922	141.275	776	950
Edenhope	5	-37.037	141.297	574	1070
Goroke	6	-36.718	141.473	504	1133
Kingston S.E.	7	-36.831	139.852	585	1018
Lucindale	8	-36.973	140.370	604	1067
Mount Burr	9	-37.542	140.456	781	965
Mount Gambier	10	-37.832	140.779	722	962
Naracoorte	11	-36.956	140.741	574	1082
Penola	12	-37.375	140.837	645	1021

The study area divided into twelve climate zones using Thiessen Polygon interpolation (Figure 7).



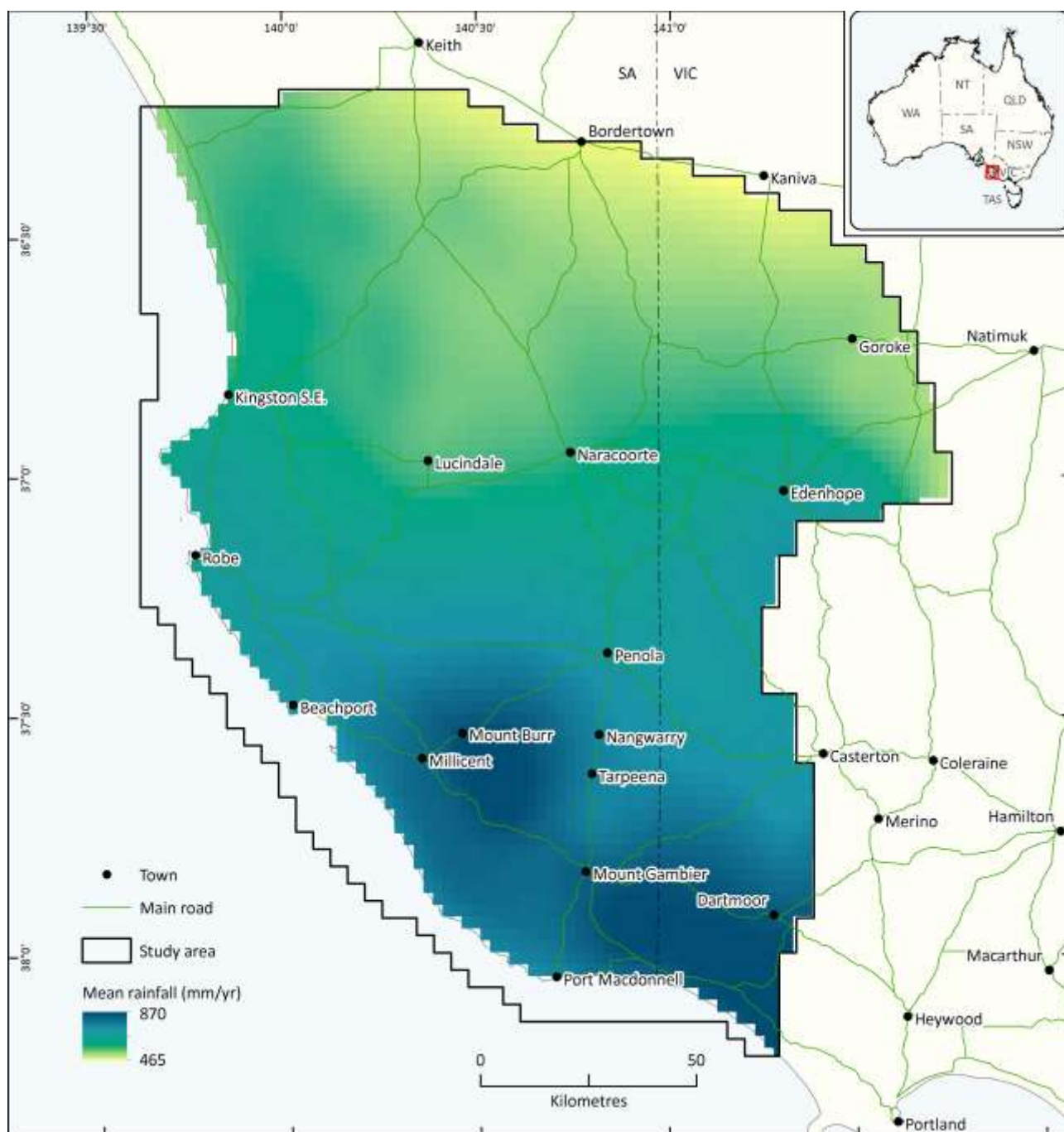


Figure 6. Mean annual rainfall across the region also showing selected climate stations for 1-D recharge modelling.

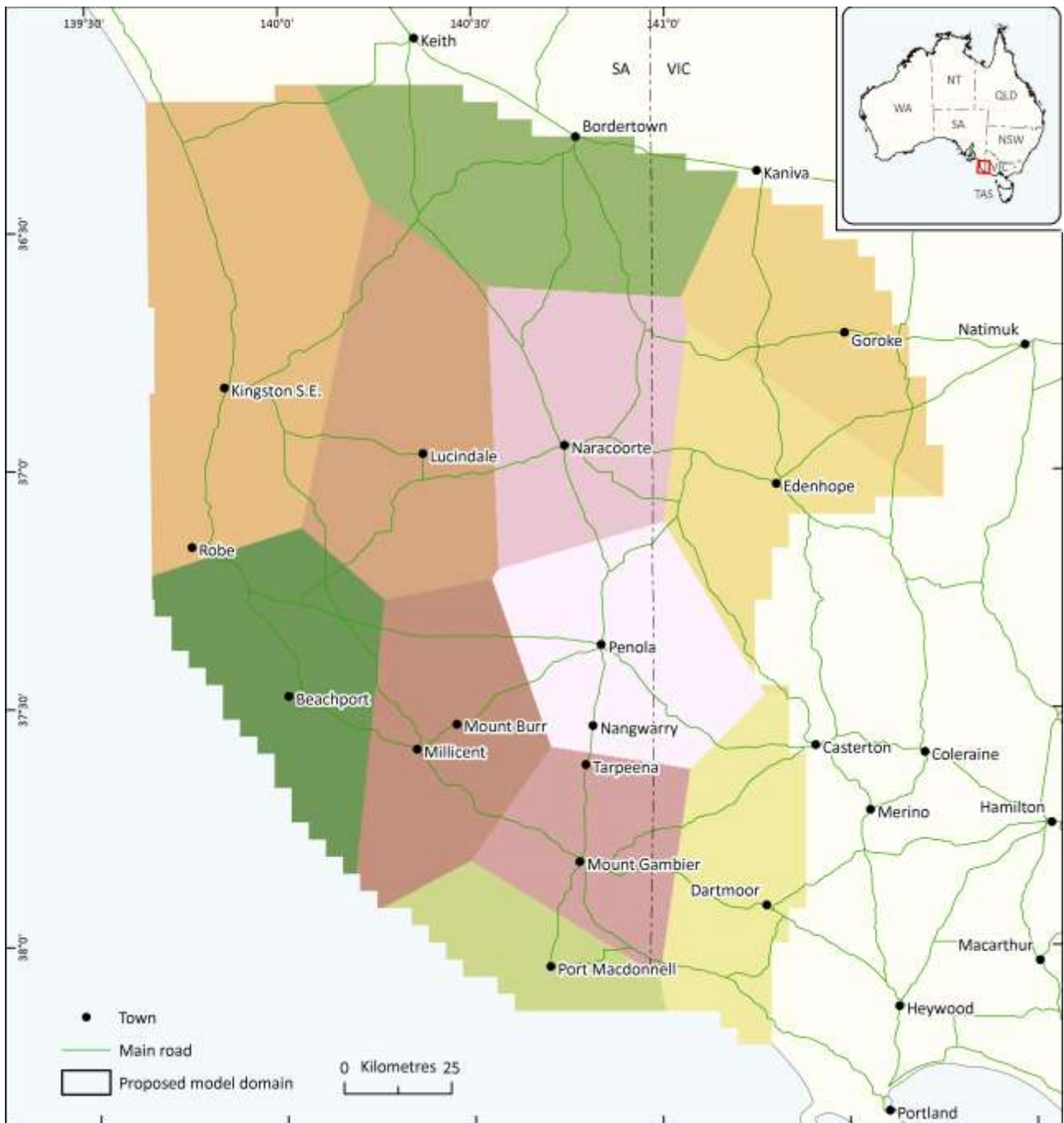


Figure 7. Thiessen polygons developed from the climate stations, used to develop the landscape key. The names of the climate stations are indicated by the town names on the map, and listed in Table 2.

## 2.4.2 SOILS

Recharge is related to the clay content of soils (Wohling et al. 2012) so the clay content of soils as mapped in ASRIS (Johnston et al. 2003) was classified into 7 classes (Figure 8). These 7 classes of soils were modelled in WAVES using the Broadbridge and White (1998) soil moisture retention curves with parameters that are representative of the clay content (Carsel and Parrish 1988). The parameters used in the modelling are shown in Table 3. The depth of soil was assumed to be deeper than the maximum rooting depth of the vegetation, therefore the soil was modelled to be a 15 metre thick layer overlying a limestone base. This was an initial estimate, which may be realistic for the upland areas north-east of Penola and Naracoorte, but soil can be as thin as 0.1 to 0.5 metres in the Mount Gambier region. For this work, only the effect of a single soil type over limestone was investigated. It may be worth looking at the impact of duplex soils, and lower soil thicknesses in the application of this method.



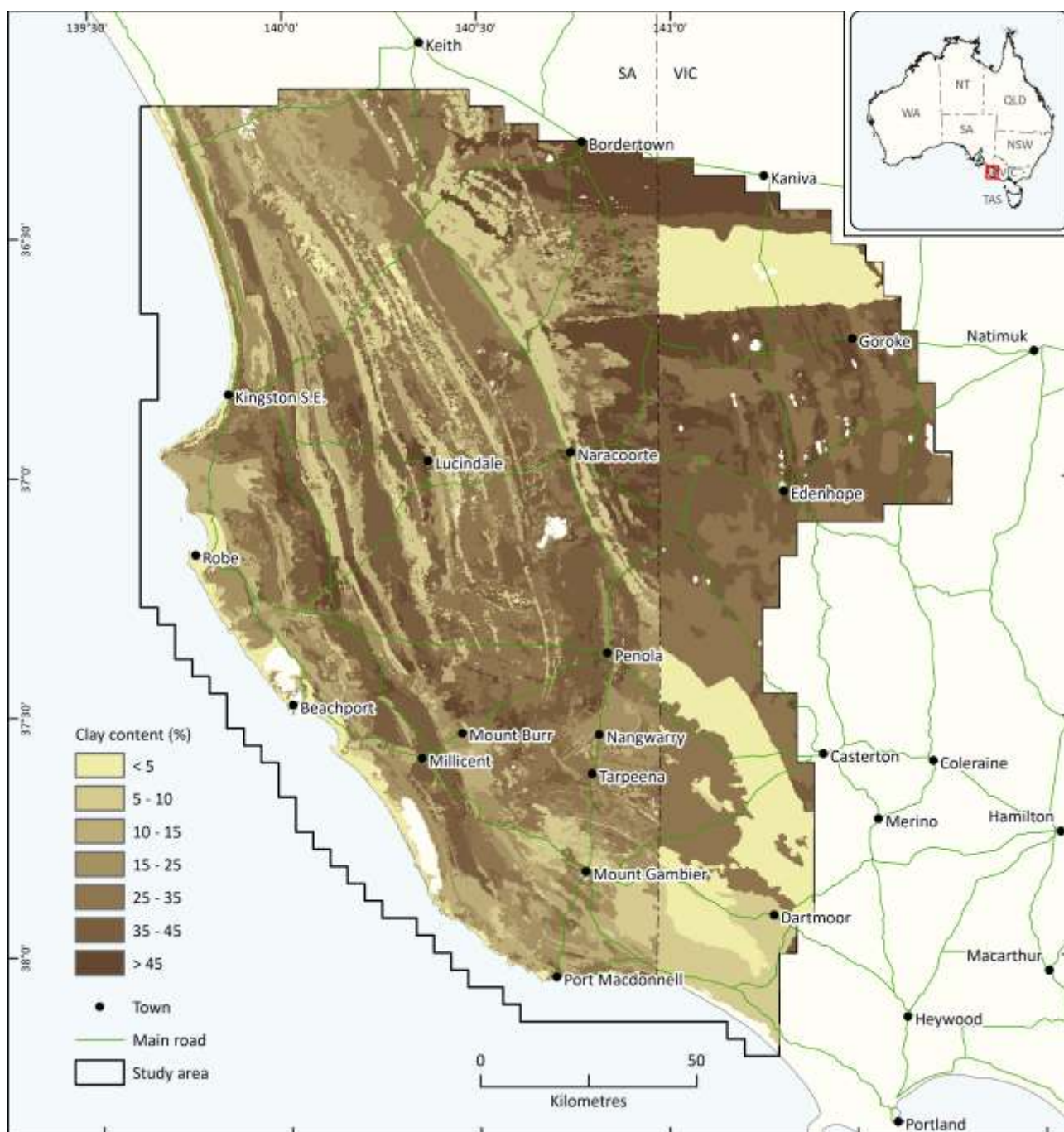


Figure 8. Soil clay content as classified into 7 classes based upon data from ASRIS (Johnston et al. 2003). Note the discontinuity at the SA/Victorian border due to different definition of soil types.

Table 3 Soil types and parameters used in the WAVES modelling (Carsel and Parrish 1988)

SOIL	% CLAY	$K_s$ (m/d)	$\theta_s$ (cm <sup>3</sup> /cm <sup>3</sup> )	$\theta_d$ (cm <sup>3</sup> /cm <sup>3</sup> )	$\lambda_c$ (m)	C
1	< 5%	3.981	0.3	0.05	0.05	1.01
2	5 – 10 %	1.585	0.35	0.1	0.05	1.02
3	10 – 15%	0.631	0.4	0.15	0.1	1.05
4	15 – 25 %	0.251	0.4	0.15	0.2	1.1

5	25 – 35 %	0.1	0.5	0.2	0.3	1.2
6	35 – 45%	$3.981 \times 10^{-2}$	0.5	0.2	0.5	1.3
7	> 45%	$1.585 \times 10^{-2}$	0.5	0.2	1.5	1.4
Limestone	-	0.1	0.2	0.1	2.5	5.0

### 2.4.3 VEGETATION TYPE

The land use was simplified from ACLUMP mapping (ABARE-BRS 2010) into 8 broad classes that were thought to produce different recharge rates (Figure 9, Table 4). This was further simplified based upon the phase 1 results that showed that we did not have enough information to distinguish hardwood plantations from softwood plantations (Crosbie and Davies 2013). In this proof of concept model, softwood and hardwood plantations are modelled using the same data, but remain separate land uses should they need to be functionally separated in future applications. The classes of irrigated, water and other have not been modelled in WAVES. The parameters used in the modelling are shown in Table 5 and are based on the parameter ranges specified within the WAVES User Manual (Dawes et al. 2004).

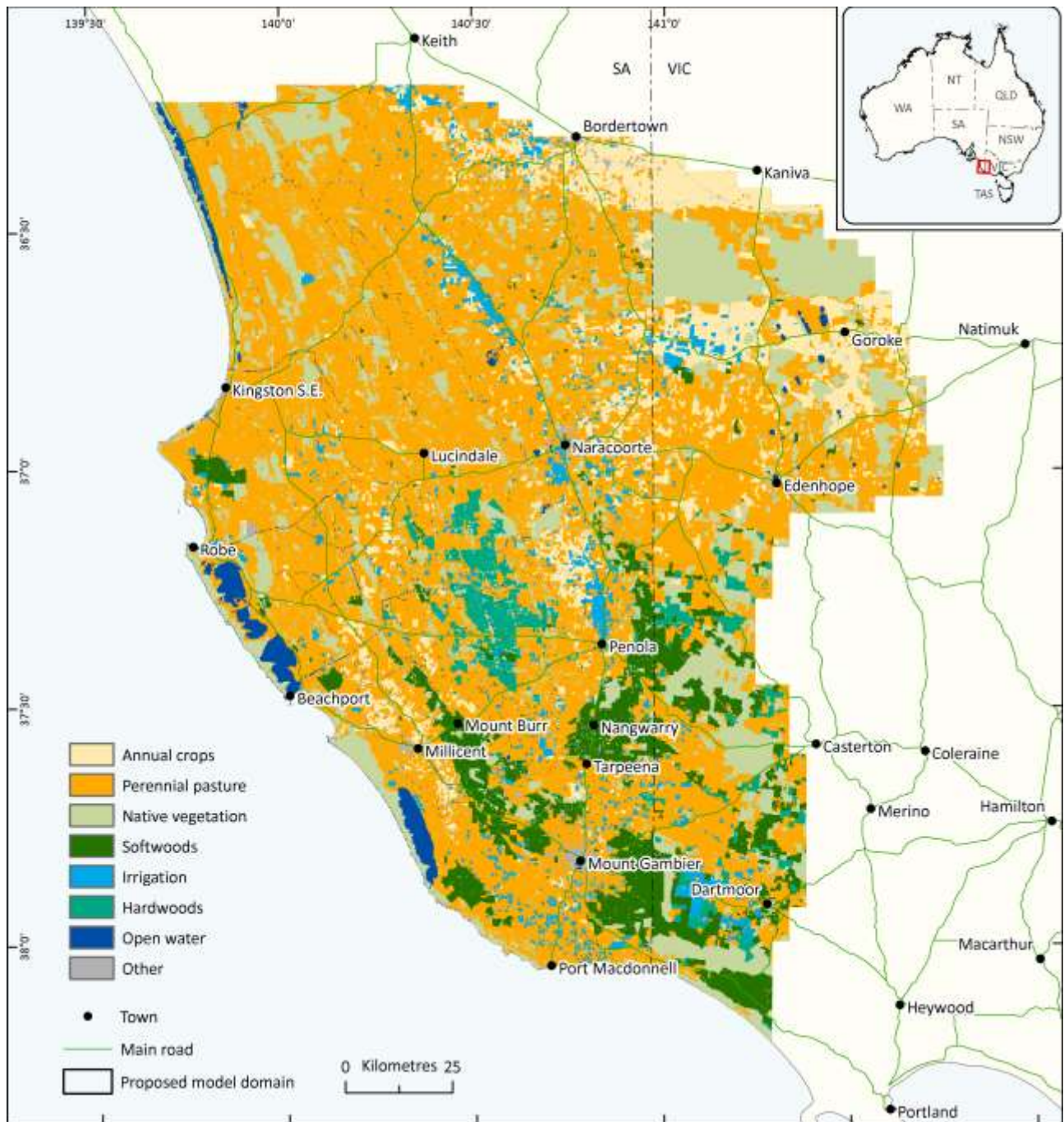


Figure 9. Land use classes from ACLUMP mapping used in the modelling based upon reclassifying data from (ABARE-BRS 2010).

**Table 4 Land use types used in the WAVES modelling**

LAND USE	LAND USE CODE	DESCRIPTION
Crops	1	Winter dominant annual crops
Perennial	2	Winter dominant perennial pasture
Native Vegetation	3	Eucalyptus overstory, winter dominant perennial understory
Softwood forestry	4	Softwood overstory, no understory
Irrigation	5	Currently using annual crops + 100 mm deep drainage. In future, use calculated irrigation rates
Hardwood forestry	6	Initially softwood overstory parameters, no understory
Open Water	8	Initially assumed to be equivalent to annual crops. Later to be modelled by the LAK package.
Other (urban, roads)	9	Initially assumed to be similar to annual crops

Table 5 Vegetation parameters used in the WAVES modelling

NO.	WAVES PARAMETER	UNIT	WINTER ANNUAL PASTURE (C <sub>3</sub> )	PERENNIAL PASTURE (C <sub>3</sub> )	NATIVE VEG OVERSTORY	NATIVE VEG UNDERSTORY <sup>1</sup>	SOFTWOODS
1	1 minus albedo of the canopy	—	0.85	0.85	0.8	0.85	0.8
2	1 minus albedo of the soil	—	0.85	0.85	0.85	0.85	0.85
3	Rainfall interception coefficient	m d <sup>-1</sup> LAI <sup>-1</sup>	0.0005	0.0001	0.0005	0.0003	0.0005
4	Light extinction coefficient	—	-0.65	-0.65	-0.45	-0.65	-0.45
5	Maximum carbon simulation rate	kg C <sup>-2</sup> d <sup>-1</sup>	0.02	0.02	0.03	0.01	0.03
6	Slope parameter for the conductance model	—	0.9	0.9	0.9	0.9	0.9
7	Maximum plant available soil water potential	m	-150	-150	-150	-150	-150
8	IRM weighting of water	—	2	1.5	2.1	2	2.1
9	IRM weighting of nutrients	—	0.5	0.5	0.3	0.5	0.3
10	Ratio of stomatal to mesophyll conductance	—	0.2	0.2	0.2	0.2	0.2
11	Temperature when the growth is 1/2 of optimum	°C	7	7	15	7	15
12	Temperature when the growth is optimum	°C	15	15	20	15	20
13	Year day of germination	d	120	-1	-1	-1	-1
14	Degree-daylight hours for growth	°C hr	16000	-1	-1	-1	-1
15	Saturation light intensity	μmoles m <sup>-2</sup> d <sup>-1</sup>	1000	1500	1500	1500	1000
16	Maximum rooting depth	m	1	1	3	1	6 <sup>2</sup>
17	Specific leaf area	LAI kg C <sup>-1</sup>	20	10	10	10	10

18	Leaf respiration coefficient	kg C kg C <sup>-1</sup>	0.001	0.001	0.001	0.001	0.001
19	Stem respiration coefficient	kg C kg C <sup>-1</sup>	-1	-1	0.0006	-1	0.0006
20	Root respiration coefficient	kg C kg C <sup>-1</sup>	0.0002	0.001	0.0001	0.001	0.0001
21	Leaf mortality rate	fraction of C d <sup>-1</sup>	0.0001	0.005	0.0005	0.005	0.0001
22	Above-ground partitioning factor	—	0.4	0.4	0.25	0.4	0.25
23	Salt sensitivity factor	—	1	1	1	1	1
24	Aerodynamic resistance	s d <sup>-1</sup>	30	30	10	30	10
25	Crop harvest index	—	0	0	0	0	0
26	Crop harvest factor	—	0	0	0	0	0

<sup>1</sup>The native vegetation class comprised of both overstory (trees) and understory (grass and shrubs) vegetation, therefore used both overstory and understory vegetation parameters.

<sup>2</sup>Where depth to water table was less than the rooting depth, the tree rooting depth was adjusted to be 1.5 times the DTWT, up to a maximum of six metres. This prevented the unintended death of the modelled trees due to anoxic conditions.



## 2.4.4 DEPTH TO WATER TABLE

The depth to water tables were modelled in WAVES as a constant head lower boundary condition. The majority of the study area had shallow water tables (Figure 10 and Figure 11) and so the discreet water table depths selected were biased to more shallow depths. There were 26 depths modelled: 0.01, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18 and 20 m depth to water table.

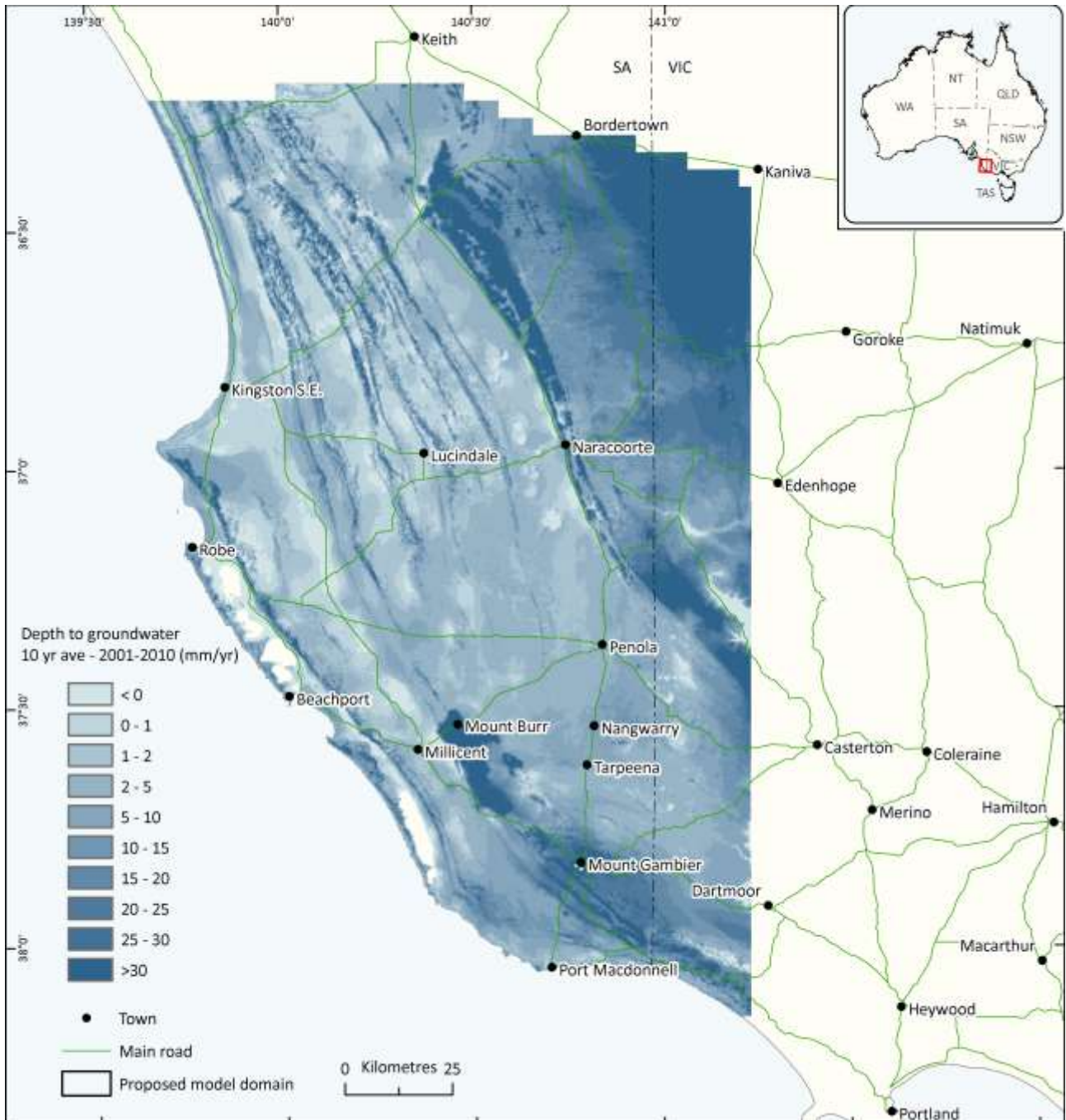


Figure 10. Average annual depth to water table (DTWT) for the years 2001 to 2010, kriged groundwater elevation measurements subtracted from a ground surface DEM. Note that the data does not completely cover the eastern extent of the model domain.

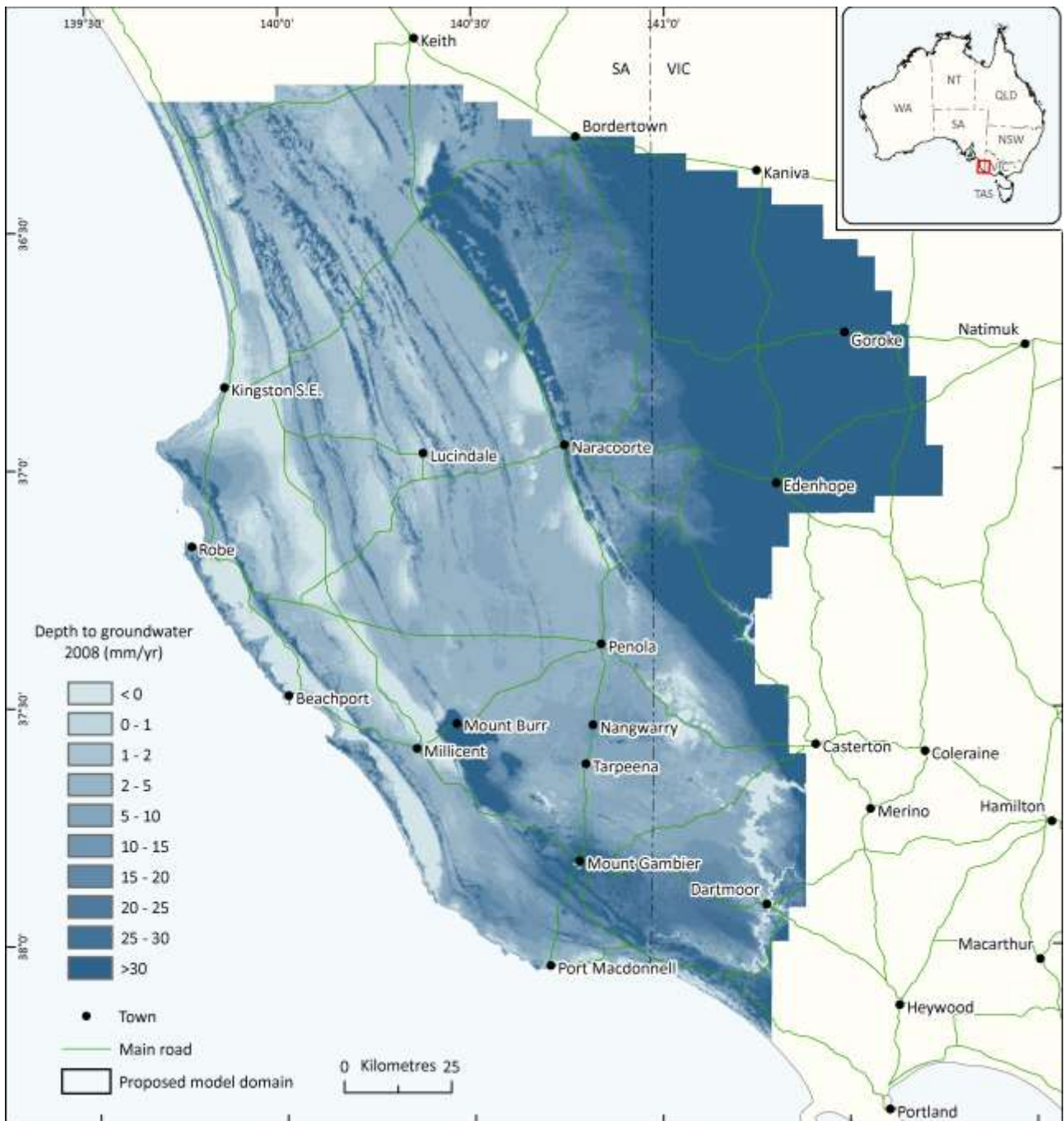


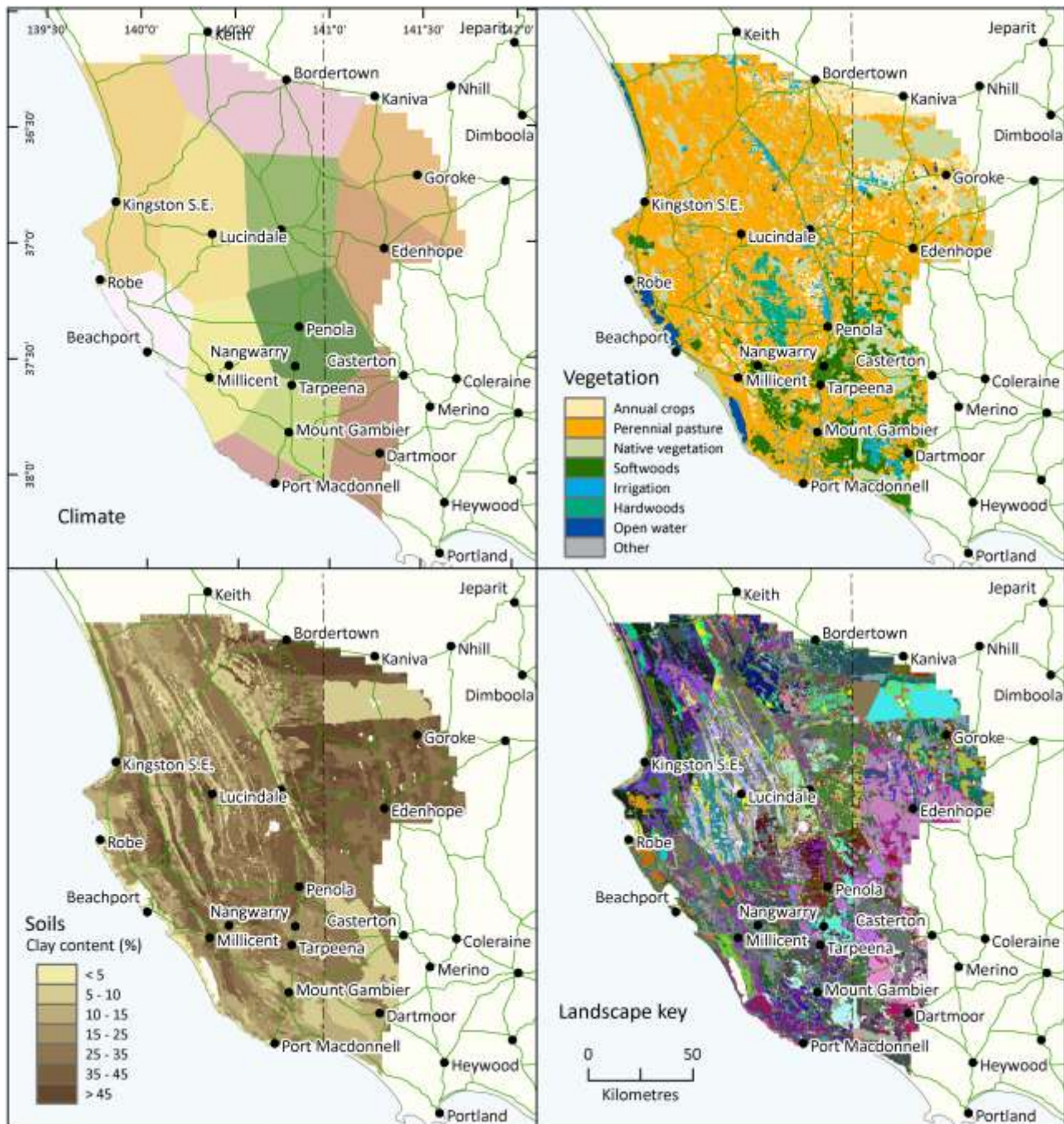
Figure 11. Average depth to water table (DTWT) for 2008 (Morgan et al. 2015): kriged groundwater elevation measurements subtracted from a ground surface DEM.

The model was spatially discretised into 99 depth nodes with a minimum spacing of 0.001 m at the first node below the surface to a maximum spacing of 0.2 m at depths greater than 2 m. The deepest node in the model is at 21 m below the surface. The first 7 m of the model domain is assumed to be soil and the remaining 14 m is assumed to be limestone. This was done as an initial representation of the system. For future use of this model, a map of soil thickness would be useful for doing additional WAVES runs for uncertainty analysis and improving recharge prediction. All the model runs were on a daily time step starting 1/1/1889 and finishing 31/12/2013. The first 25 years of the simulation were discarded as a model spin-up period and the remaining 100 years were reported as the long term average.



## 2.5 Landscape key and net recharge lookup table development

The landscape key was developed using information on proximity to meteorological stations (Figure 7), soil type (Figure 8) and vegetation type (Figure 9). A set of 672 unique identifier codes was developed from these three determinants (Figure 12). Each cell of the MODFLOW model was assigned one of the identifier codes.



**Figure 12 Development of the landscape key, with (a) climate, (b) vegetation and (c) soil information, resulting in (d) unique identifier codes.**

Results from the 17 000 WAVES runs were collated into one net recharge vs depth to groundwater function for each unique landscape key, then aggregated into a lookup table.

## 2.6 MODFLOW modification

The MODFLOW ETS package was modified to obtain net recharge (gross groundwater recharge minus groundwater evapotranspiration) from the lookup table. The net recharge or NRF package takes the groundwater head at each cell and calculates depth to groundwater by subtracting groundwater head elevation from the surface elevation. The landscape key is used to identify which net recharge vs. depth to groundwater data set to use and the net recharge is obtained for each cell by a linear interpolation between net recharge for the closest depth to groundwater above and below the MODFLOW generated groundwater depth.

This value of net recharge is added to the right hand side (RHS) component of the MODFLOW governing equation (Harbaugh et al. 2000), and groundwater elevation and net recharge are solved for iteratively. Once the head iteration has stabilised, the net recharge is printed to the water budget of the .lst file and in the case of a transient model, the model begins the iteration process for the next time step.

The flexibility of the process lies in the ability for the model to run as either steady state (as is described in this report) or as a transient process (a potential future use), with both the landscape key and the lookup table to change for each stress period. This allows net recharge to be input into steady state models, as a seasonally changing input, or as a historical or synthetically generated data record. Changes in land use may be incorporated by changing each cell's landscape key, and climate shifts can be modelled by changing the lookup table inputs in time.

Detailed instructions for developing the MODFLOW NRF input files are found in Appendix A .

## 2.7 Model testing

The modelling process was tested in three stages. Initially, the WAVES model was tested by using a static watertable to convert the net recharge lookup table into a spatial realisation of net recharge for the study area. The parameterisation of the WAVES model was adjusted during this process to produce a net recharge distribution and spatial mean similar to the MODIS/CMRSET net recharge map from the Phase 1 report.

The modified MODFLOW NRF package was tested on a simple 17 by 17 cell, five layer MODFLOW tutorial model, based on that provided in the LAK package documentation. The lookup table used in the NRF package was developed to mimic the behaviour of the EVT and RCH packages used in the comparison standard MODFLOW model.

Finally, a lookup table and landscape key were developed for the study site, and resulting net recharge outputs from the WAVES-MODFLOW were compared with those from the regional MODFLOW model described in (Morgan et al. 2015).

## 3 Results

### 3.1 WAVES outputs

The output fluxes from the WAVES model runs were compiled into flux-DTW relationships (Figure 13 and Figure 14) for each climate, soil and vegetation combination.

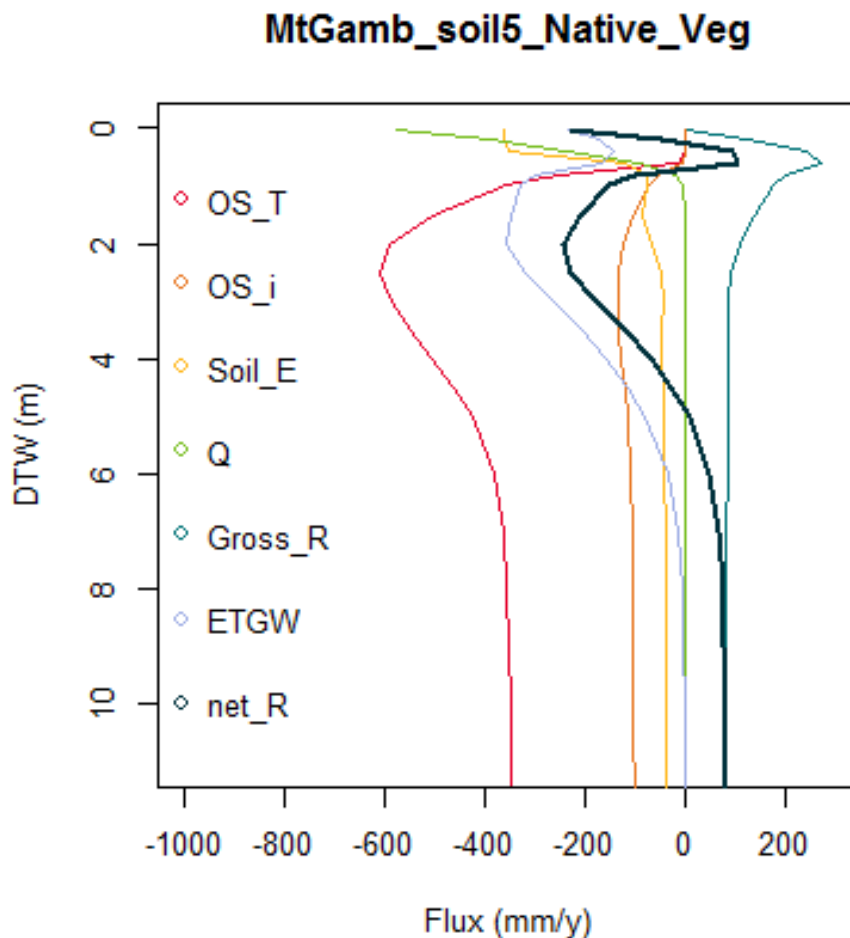


Figure 13 Example depth vs. flux curves generated from WAVES modelling for Mount Gambier native vegetation on Soil type 5, showing overstory transpiration from both soil and groundwater (OS\_T), overstory interception (OS\_i), evaporation from the unsaturated zone (Soil\_E), runoff (Q), gross recharge (Gross\_R), evapotranspiration directly from groundwater (ETGW) and net recharge (net\_R). Note that transpiration was higher than found in previous field studies.

Overstory transpiration, OS\_T (red), includes water transpired from both the unsaturated zone and groundwater. When the watertable is close to the surface, anoxic conditions result in poor vegetation health or death, and therefore zero water use. Transpiration increases with depth to watertable to a maximum flux just below two metres. This is where vegetation can access moisture from the unsaturated zone (infiltrated water) and during times of low rainfall, the capillary fringe from shallow groundwater will provide all vegetation water requirements. As the depth to water table increases the suction required for vegetation to use groundwater is higher, therefore less groundwater is used. Once the capillary fringe is below the rooting depth, groundwater is no longer accessible to vegetation and the transpiration

asymptotes to the flux that is obtained from unsaturated zone moisture alone. Therefore the total transpiration remains less than zero beyond the depth to which vegetation will affect soil moisture. Transpiration is influenced by DTWT to a depth of around ten metres. The transpiration – DTWT curves are very similar in shape to those of riparian vegetation described in Baird et al. (2005) and Baird and Maddock III (2005). In the case of Figure 13, the rate of transpiration is higher than has been found in previous studies of native vegetation groundwater use (Mustafa et al. 2006; Leaney et al. 2006).

Interception (orange) also changes with depth. Interception of rainfall and subsequent evaporation of the intercepted water is highly dependent on leaf area index (LAI), a measure of the density of leaves present. LAI is a function of depth, similarly to transpiration, where LAI is zero when the DTWT is at the surface due to dead vegetation, and highest at around two to three metres where vegetation is using groundwater as an unlimited water source.

Understory transpiration and interception are also modelled for the native vegetation but are not shown in Figure 13 to aid in clarity.

Soil evaporation (yellow) is the water evaporated from the soil surface and includes both infiltrated water within the unsaturated zone and when the water table is near the surface, evaporation from groundwater through the capillary fringe. The soil evaporation curve is similar to those shown in Talsma (1963) and Gardner and Fireman (1958), and is influenced by DTWT to a depth of around two metres.

Gross recharge (mid-blue) was defined as the downward water flux from the unsaturated zone across the water table. It is zero when the watertable is at the ground surface and there is insufficient empty pore space within the unsaturated zone to accept infiltrating water. When the soil profile is saturated, any additional water that would normally infiltrate becomes runoff, Q (green). In this case, runoff occurs when the watertable is within one metre of the ground surface. Gross recharge increases to a maximum at DTWT of around one metre, as a large proportion of infiltrating water will reach the water table without being evaporated or transpired from the unsaturated zone. As the DTWT increases, the opportunity for infiltrating water to be evaporated or transpired increases, and recharge reduces to a value that is constant with depth. For this example, recharge is influenced by the DTWT to about 2.5 metres. This critical depth is different for various other combinations of soil type and vegetation coverage. The gross recharge – DTWT curve is similar to those described for the Warrego sand aquifer (Crosbie 2003).

Net recharge (dark blue) was calculated to be gross recharge minus ET from the groundwater, defined as the upward flux across the water table. Net recharge combined the characteristics of recharge and evapotranspiration, and is generally negative (ET dominated) for shallow DTWT, and positive (recharge dominated) where the water table is deeper. In this example, net recharge is influenced by DTWT to around 8 metres. The shape of the forestry net recharge curve is similar to the box plots for forestry shown in the Phase 1 report (Crosbie and Davies 2013), although it is higher in magnitude than previous studies such as Mustafa et al. (2006) and Leaney et al. (2006).

Due to the relatively large 1000 m x 1000 m MODFLOW model cells in the regional model, it was assumed that a proportion of runoff (Q) when the water table was shallow would re-infiltrate in another part of the cell. For this report, due to the relatively large cell size and flat topography, it was assumed that all of the runoff is converted to recharge within other parts of the same cell. It was therefore added to the gross recharge and net recharge as shown in Figure 13 to Figure 14. It is possible to change the proportion of re-infiltrating runoff for the entire model or for different regions of the model during formal calibration if necessary.

Some general principles could be summarised from the flux – DTWT relationships, common examples of which are shown in Figure 14.

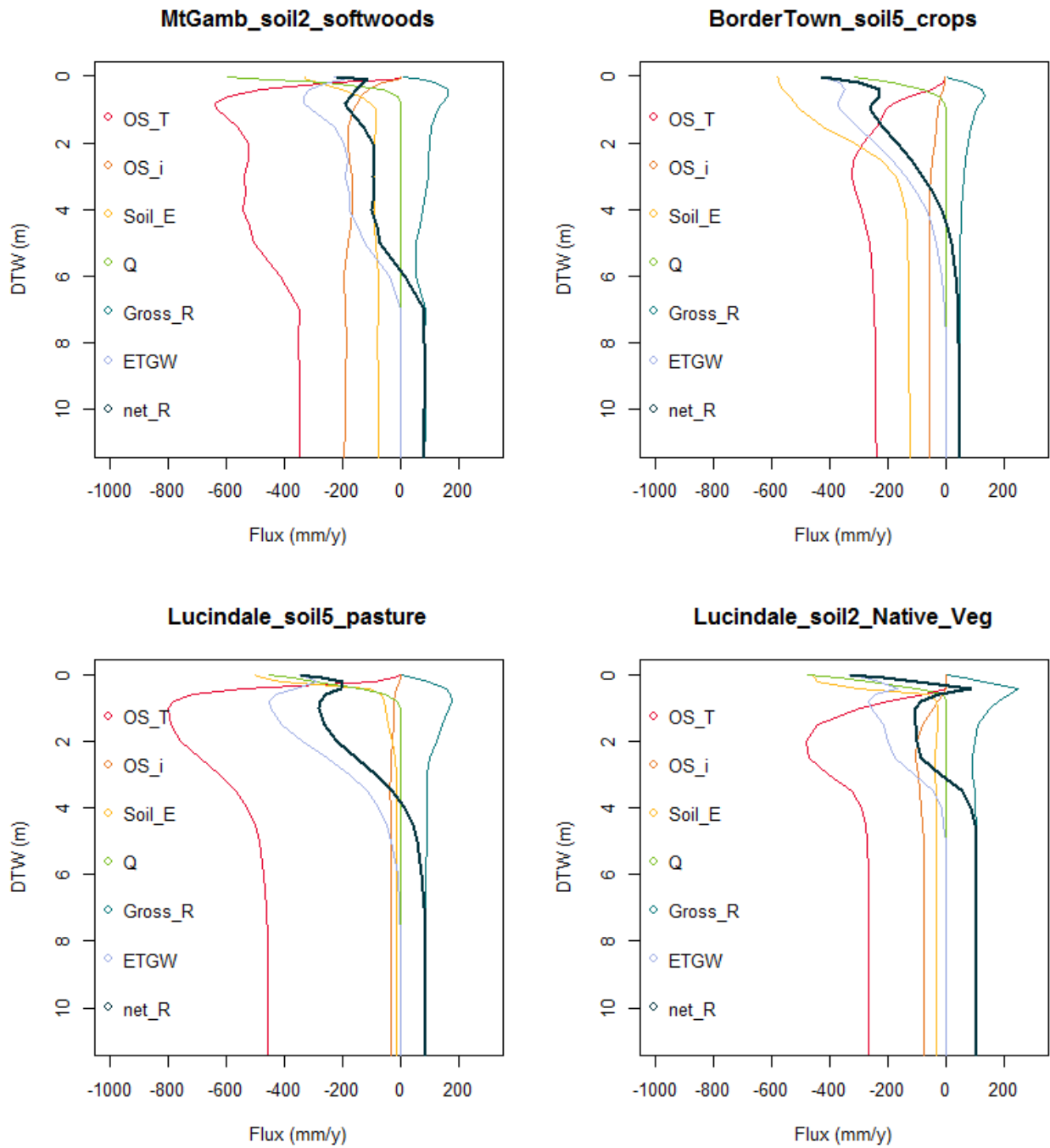


Figure 14 Example groundwater depth vs. net recharge curves generated from WAVES modelling for (a) Mount Gambier Softwoods on Soil type 2, (b) Bordertown crops on soil type 5, (c) Lucindale perennial grazing on soil type 5 and (d) Lucindale Native vegetation on soil type 2. Net recharge is indicated by the black line. Other unsaturated zone fluxes used to calculate net recharge are also shown: transpiration (OS\_T, red), canopy interception (OS\_i, orange), soil evaporation (Soil\_E, yellow), runoff (Q, green), gross recharge (Gross\_R, light blue) and ET from groundwater (ETGW, purple). Note that transpiration rates for native vegetation were higher than found in previous field studies.

Transpiration from softwoods, generally found in the southern parts of the study site on sandy soils, was high and remained high for DTWT in much of the soil profile down to just below the pre-defined six-metre rooting depth (Figure 14a). The maximum transpiration rate (approx 600 mm/yr) is similar to those reported in Benyon et al. (2006), and the recharge to deep groundwater (80 mm/yr) is similar to the MODIS/CMRSET data around Mt Gambier in the Phase 1 report (Crosbie and Davies 2013).



Soil evaporation was very high for crops, which were predominantly found on heavier soils in the drier northern part of the study site. This is likely to be due to the high rates of PET and the bare ground or stubble during summer months (Figure 14b). Transpiration is also lower as the vegetation is only present for the cooler months of the year.

Pastures, which were the dominant land coverage for the region, had high rates of transpiration with shallow DTWT (Figure 14c). The example shown is characteristic of perennial pastures in the heavy soils of the interdunal flats near Lucindale. The higher percentage of clay in these soils allows moisture to be held within the soil profile and available for vegetation use longer into the drier months than in the adjacent sandy dunes. The heavier clay soils and larger capillary fringe also allow perennial vegetation to use groundwater with a much deeper DTWT than sandy soils.

It should be noted that this modelling does not account for salinity, therefore transpiration in this area may be limited by water quality and lower than that shown.

Native vegetation was often present on the tops of the sandy dunes near Lucindale (Figure 14d). Transpiration from the unsaturated zone (red, flux rate with DTWT below 6 metres) is lower than for pasture on heavy soil (Figure 14c) as infiltrating water moves quickly through the sand system to recharge the groundwater.

While the shapes of the curves match those found in the literature, the magnitude of net recharge was higher than those rates measured in the field. Further calibration of the WAVES model is necessary before this method is used to inform resource allocation.

A comparison of net recharge – DTWT curves for seven soil types and four land covers is provided for the Mount Gambier region in Appendix D .

### 3.2 Testing net recharge with a static water table

The net recharge – DTWT functions were aggregated to provide a lookup table and landscape key that were used by the modified MODFLOW model for the region (Appendix B and Figure 12d).

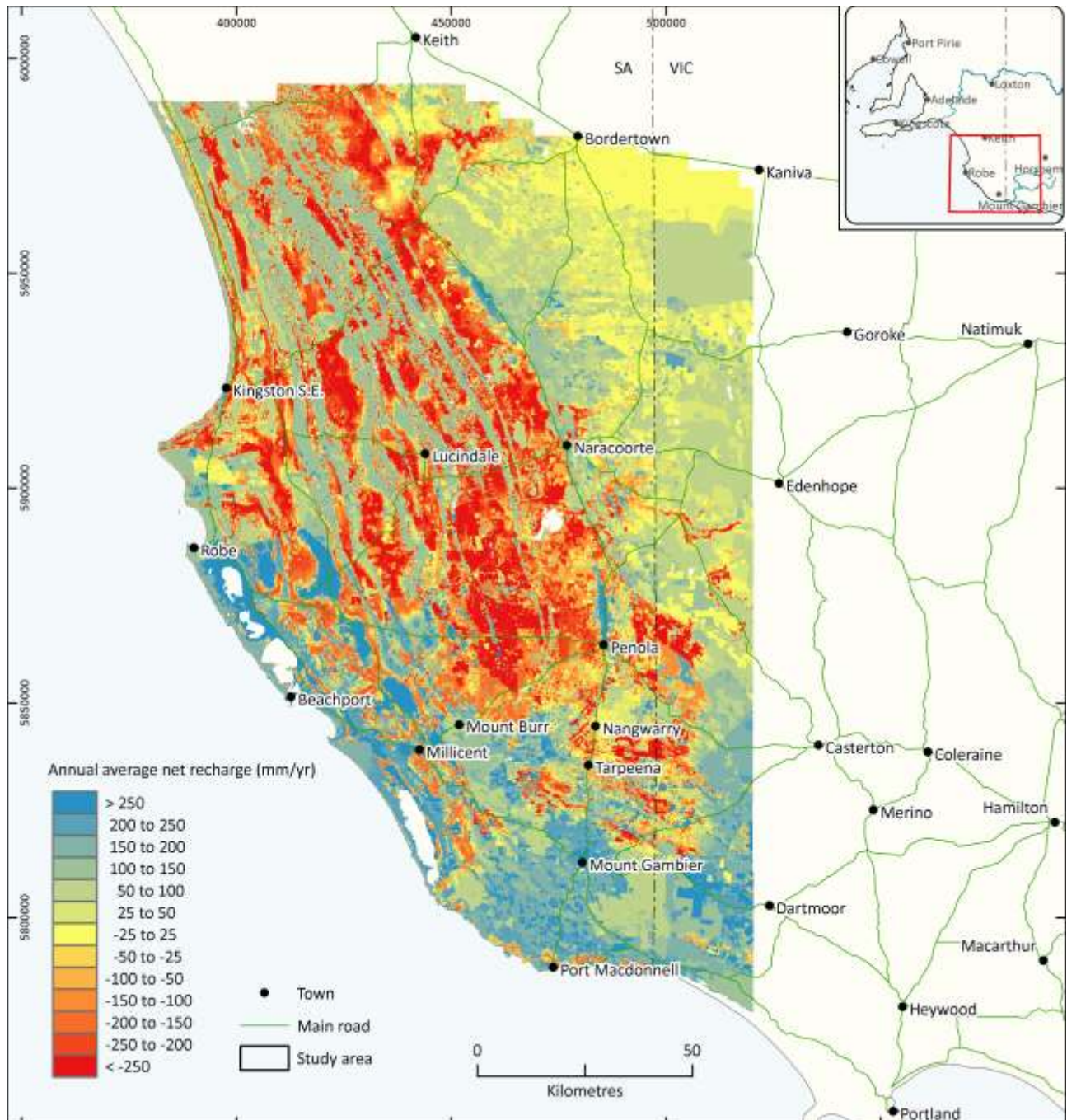
In order to quickly test and improve the WAVES vegetation input parameters, a static depth to groundwater raster was used as a preliminary groundwater estimate to compare mean annual net recharge from the WAVES model and the MODIS/CMRSET data from the Phase 1 report. Outputs are shown for the following scenarios:

- Mean annual net recharge from the WAVES modelling using composite 2001 – 2010 groundwater elevation data (Figure 15)
- Mean annual net recharge from the WAVES modelling using the 2008 static groundwater elevation data (Figure 17)
- Mean annual net recharge from the WAVES modelling using the 2008 static groundwater elevation data with modified vegetation parameters to improve the match between net recharge – DTWT curves and recharge and ET values found for the region in previous studies (Benyon et al. 2006; Crosbie et al. 2015) (Figure 18)

For the WAVES outputs, as expected, the net recharge was found to be sensitive to depth to watertable, with positive net recharge (recharge) occurring in areas with deeper groundwater (Bordertown to north east of Naracoorte and South of Mount Gambier) and high rates of ET where groundwater is shallow, mostly within the inter-dunal flats in the western part of the region (Figure 15). Irrigation districts north of Penola and north west of Naracoorte show up with high rates of recharge as applied water plus infiltrating precipitation exceed crop water use. Forestry areas south east of Mount Gambier and south of Mt Burr show lower recharge than surrounding areas, and other forestry areas east and west of Penola where groundwater is shallower show net ET. The mean net recharge for the region, to give an overall indication of regional performance, is 14.7 mm/yr.

In comparison, however, the MODIS/CMRSET data indicates that net ET is distributed more evenly across the study site. However in some areas, net recharge was observed at the inter-dunal flats on the western

side of the study site, for example just east of Kingston S.E. (Figure 16). Irrigated areas are shown as having moderate to high ET, as the waterbalance calculation used to produce this data did not account for applied irrigation. Forested areas east of Penola and south of Lucindale show high net ET, while those over a deeper water table near Mt Burr and Mt Gambier show moderate net ET. The mean net recharge for the study site, adjusted to not include the eastern section not included in the composite STWT data, is 40 mm/yr.



**Figure 15 Mean annual net recharge from WAVES modelling using composite 2001 – 2010 DTWT data. Mean is 14.7 mm/yr.**

While the lookup table was developed using annual average data over a 100-year averaging period, the net recharge for the 2008 depth to groundwater map was calculated using WAVES in order to compare the results with those developed within this project by Flinders University (Figure 17). The spatial distribution of net recharge was similar to that calculated with the composite DTWT data, but due to the deeper groundwater following a long period of drier than average climate, the average net recharge for the region was higher, at 43.5 mm/yr. Attempts to adjust vegetation parameters to match the net recharge-DTWT



curves from Phase 1 of the project and previous studies (Benyon et al. 2006; Crosbie et al. 2015) produced a lower regional average of 20.8 mm/yr (Figure 18), but this also produced more extreme recharge and ET, and was still not as low as the CMRSET average net ET rate with the 2008 DTWT of -36.6 mm/yr (Figure 19).

For a true and accurate comparison between WAVES and MODIS/CMRSET model results 2008, additional WAVES output processing would be required to produce curves specifically for 2008. This may require soil moisture information for accurate water balance calculations using the MODIS data. For this project it was deemed more important to ensure that the methodology first worked on test models and the regional model, rather than calibrating vegetation and climate parameters. Further calibration is required before the data may be used for resource allocation purposes.

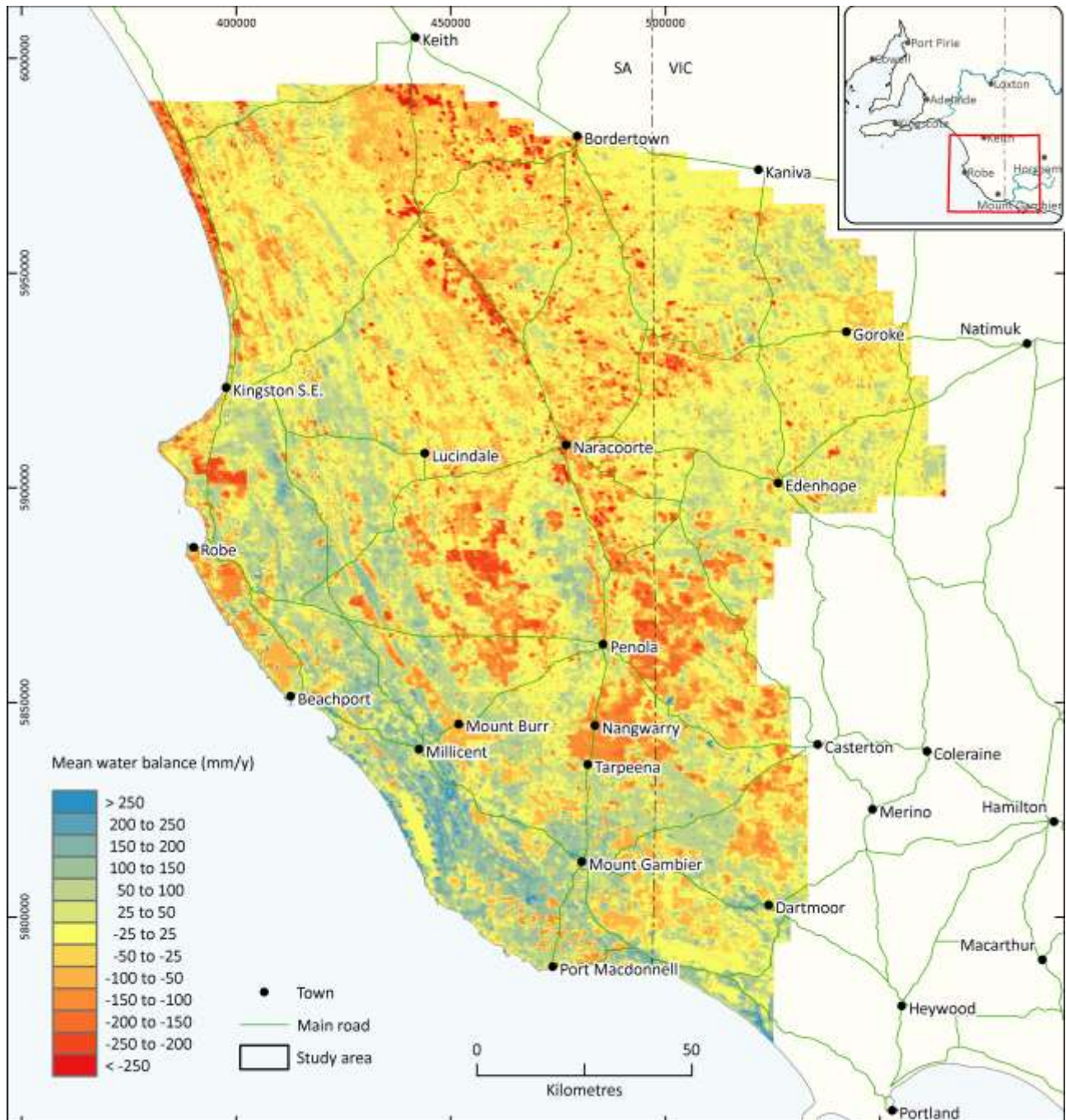


Figure 16 Mean net recharge from water balance analysis of MODIS satellite data using CMRSET algorithms, composite 2001 - 2010. Mean is 40 mm/yr (adjusted to not include the eastern strip not modelled in Figure 15).



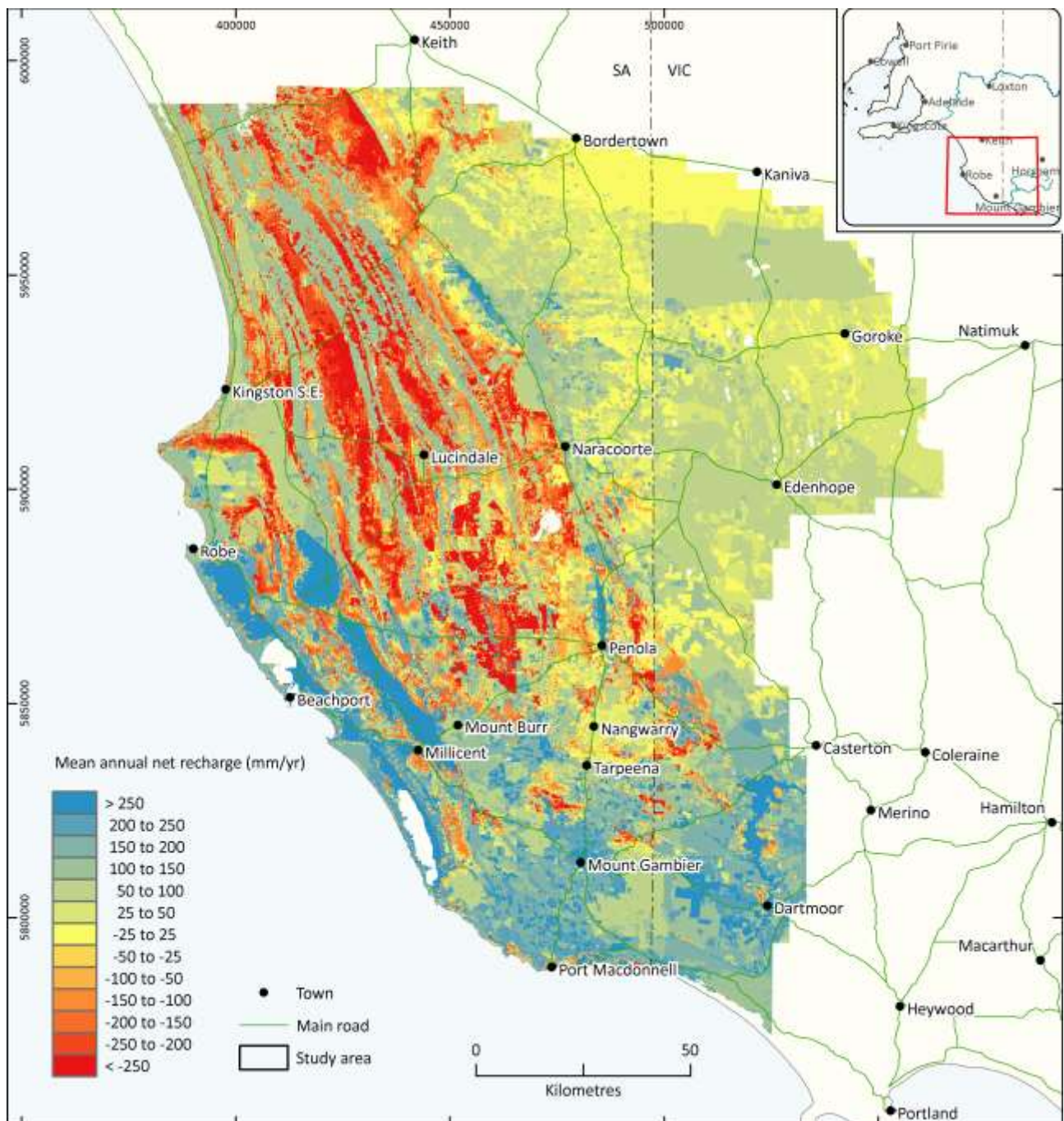


Figure 17 Mean annual net recharge from WAVES modelling using the 2008 average static watertable. Mean is 43.5 mm/yr

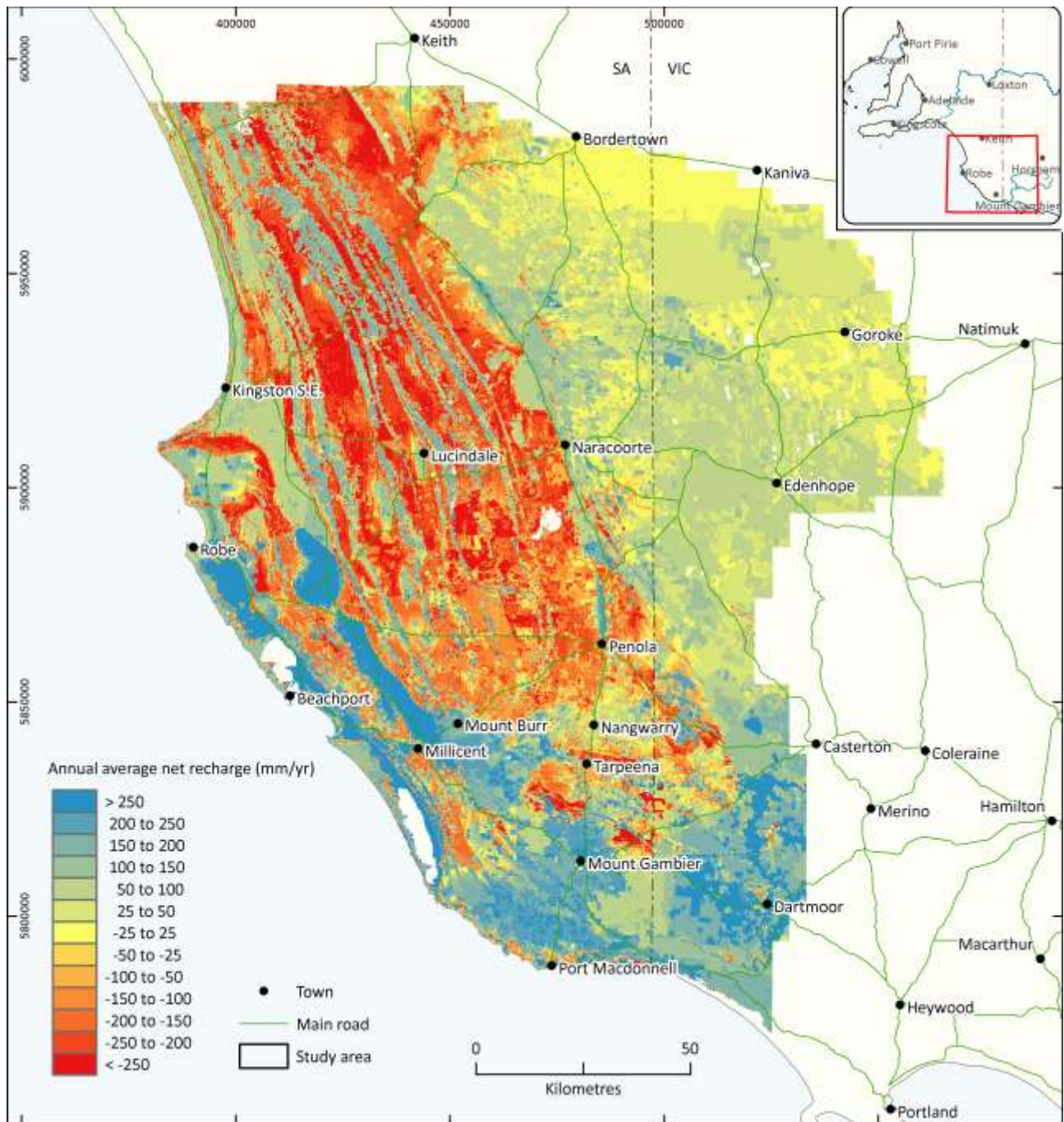


Figure 18 Mean annual net recharge from WAVES modelling using the 2008 average static watertable and updated vegetation parameters. Mean is 20.8 mm/yr



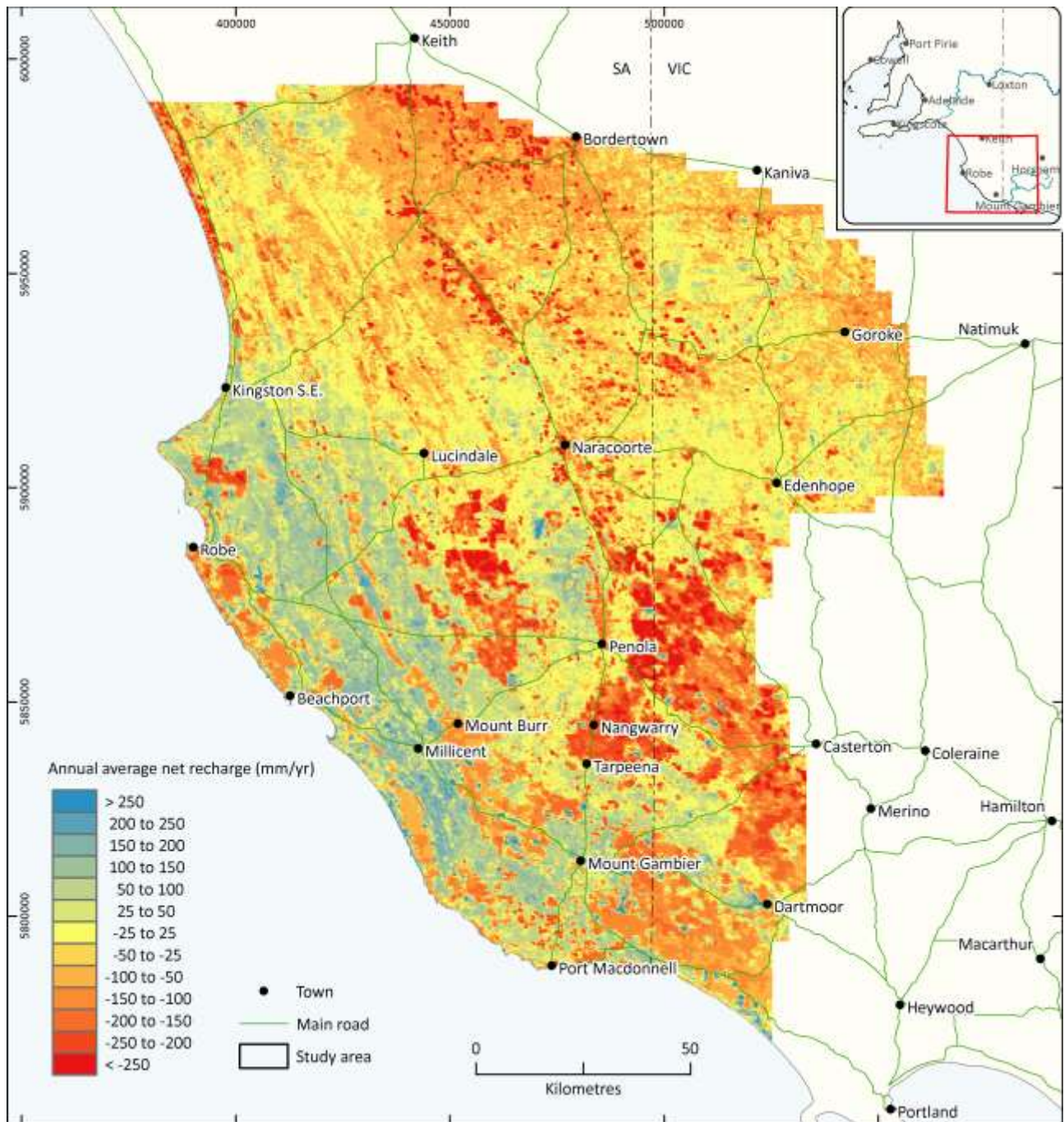


Figure 19 Mean net recharge from water balance analysis of MODIS satellite data using CMRSET algorithms, 2008. Mean is -36.6 mm/yr

### 3.3 Modifying the MODFLOW model

The modified MODFLOW model was tested against a small model modified from the tutorial example in the documentation for the LAK3 package. The model had 17 x 17 cells and 5 layers, with a surface that sloped from west to east (Figure 20).

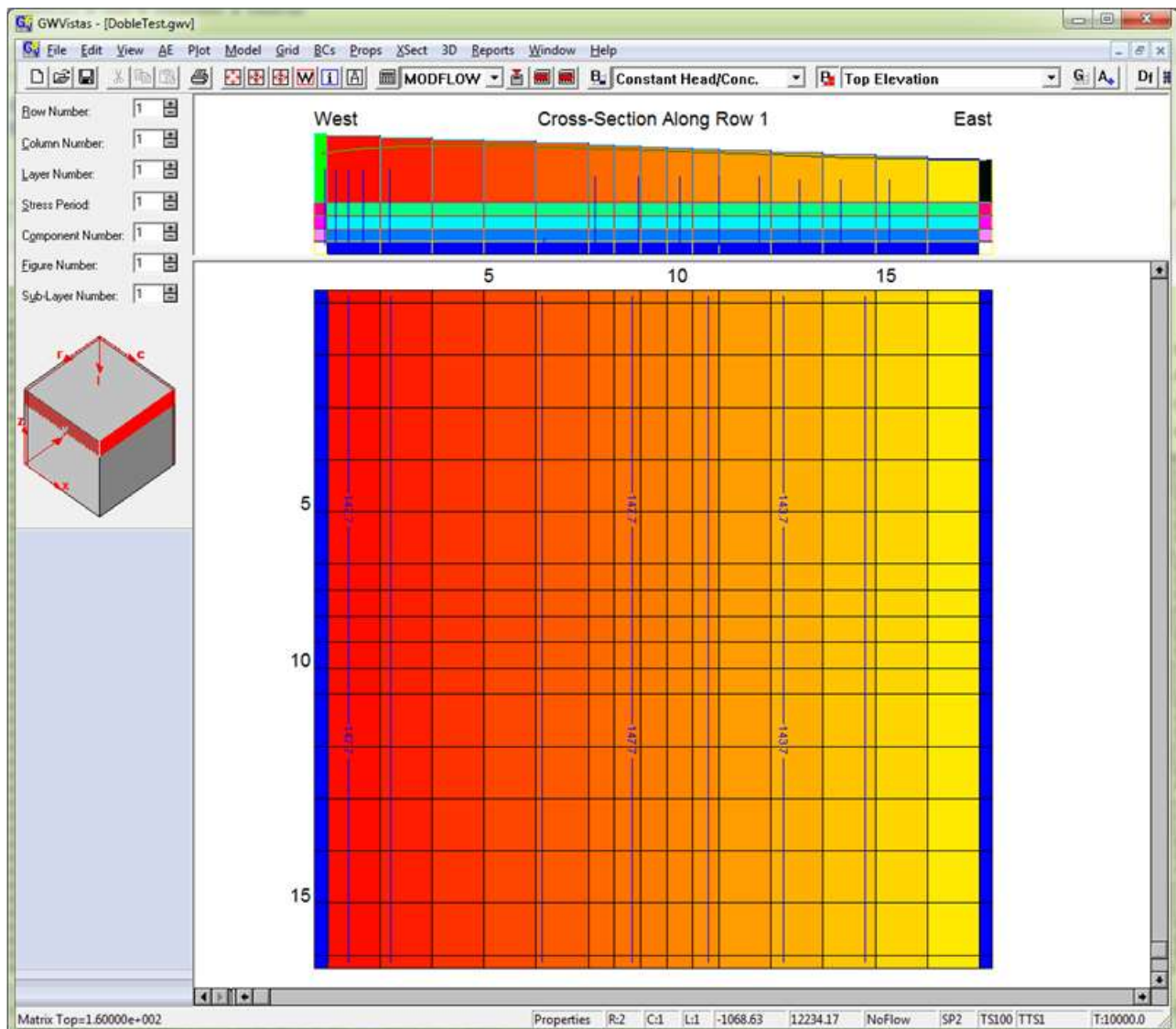


Figure 20 The test model used to confirm performance of the new MODFLOW Net Recharge Function (NRF) package

The model was run with the original ET and recharge functions, and with a lookup table that represented the combination of these two functions. Results from the Net Recharge Function (NRF) model were identical to the unmodified MODFLOW model for recharge and ET separately, and very close when the recharge and ET functions were applied together. These outcomes suggested that the modified model was processing the lookup functions correctly.

### 3.4 Outputs from the South East model.

Using the lookup table and land use key developed above and the ET surface from the MODFLOW EVT package, the modified MODFLOW code was run and compared with the steady state version of the regional model described in Morgan et al. (2015). At this stage the WAVES-MODFLOW model did not converge in steady state, so a 1000 year long, 1000 timestep transient run using steady state inputs at each time step was used as a proxy for steady state. The results show a flatter, lower water table in the lowland (western) areas of the South East, and a steeper hydraulic gradient in the highland (eastern) area for the modified WAVES-MODFLOW model (Figure 21) than the regional model described in model development report (Morgan et al. 2015), which used just the recharge (RCH) package (Figure 22). Although a formal model calibration using the WAVES net recharge-DTWT functions has not yet been performed, this piezometric surface appears to improve the representation of system behaviour in the lowland and upland areas of the South East model, compared with the groundwater surface interpolated from bore measurements (Figure 23).

The resulting piezometric surface resulted in a lower drain discharge volume (50%), lower net ET (23%) and lower net recharge (55%) in the .lst file water budget than for the regional modelling (Table 6). Interestingly, the output from the production wells was slightly lower in the WAVES-MODFLOW model results than for the unmodified MODFLOW model. This may be due to the water table being below the screen depth of some of the wells, as dry cells will cause pumps to switch off. It could suggest that the watertable is slightly too low in this model run. Inflow across constant head boundaries was 32% of the unmodified MODFLOW model while outflow across constant head boundaries was similar, at around 69% of the unmodified flux. Overall, the average net recharge flux for the model was 82 mm/yr. This is significantly higher than the 14.7 mm/yr estimate using the static water table or the 40 mm/yr estimate from the CMRSET data. The estimate from the regional unmodified MODFLOW model output, in comparison, was 130 mm/yr.

The modified MODFLOW NRF package was demonstrated to converge for the South East regional model, but further calibration will be required to test and improve recharge and ET estimates.

**Table 6 Water budget for the South East comparing results from the modified WAVES-MODFLOW model and regional South-East MODFLOW model from Morgan et al. (2015).**

	WAVES-MODFLOW	Regional MODFLOW model	WAVES-MODFLOW results as a fraction of results from regional model
IN	(m <sup>3</sup> /d)	(m <sup>3</sup> /d)	(%)
Constant Head	42,165	131,131	32
Net Recharge	6,278,055	11,330,250	55
OUT			
Constant Head	4,571,627	6,586,336	69
Wells	141,944	152,216	93
Drains	1,279,215	2,551,208	50
Net recharge (net ET)	502,637	2,171,615	23

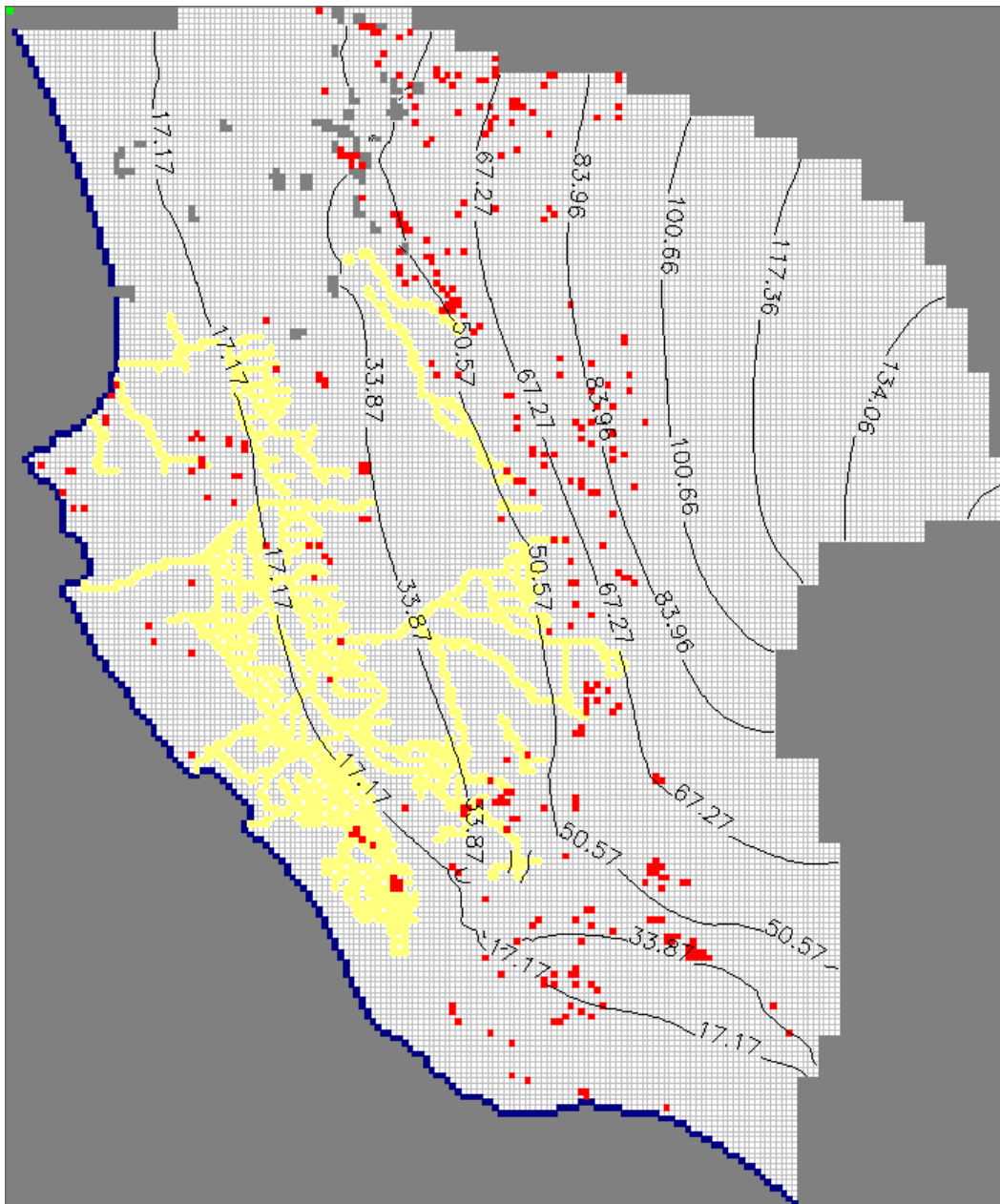


Figure 21 Groundwater head output from the layer 1 of the WAVES-MODFLOW model using the net recharge lookup function. The groundwater head is lower in the low-lying part of the study site, there is a break of slope at the Kanawinka Fault and it is pinched in around the Tartwaup Fault. See Figure 4 for locations of the faults.



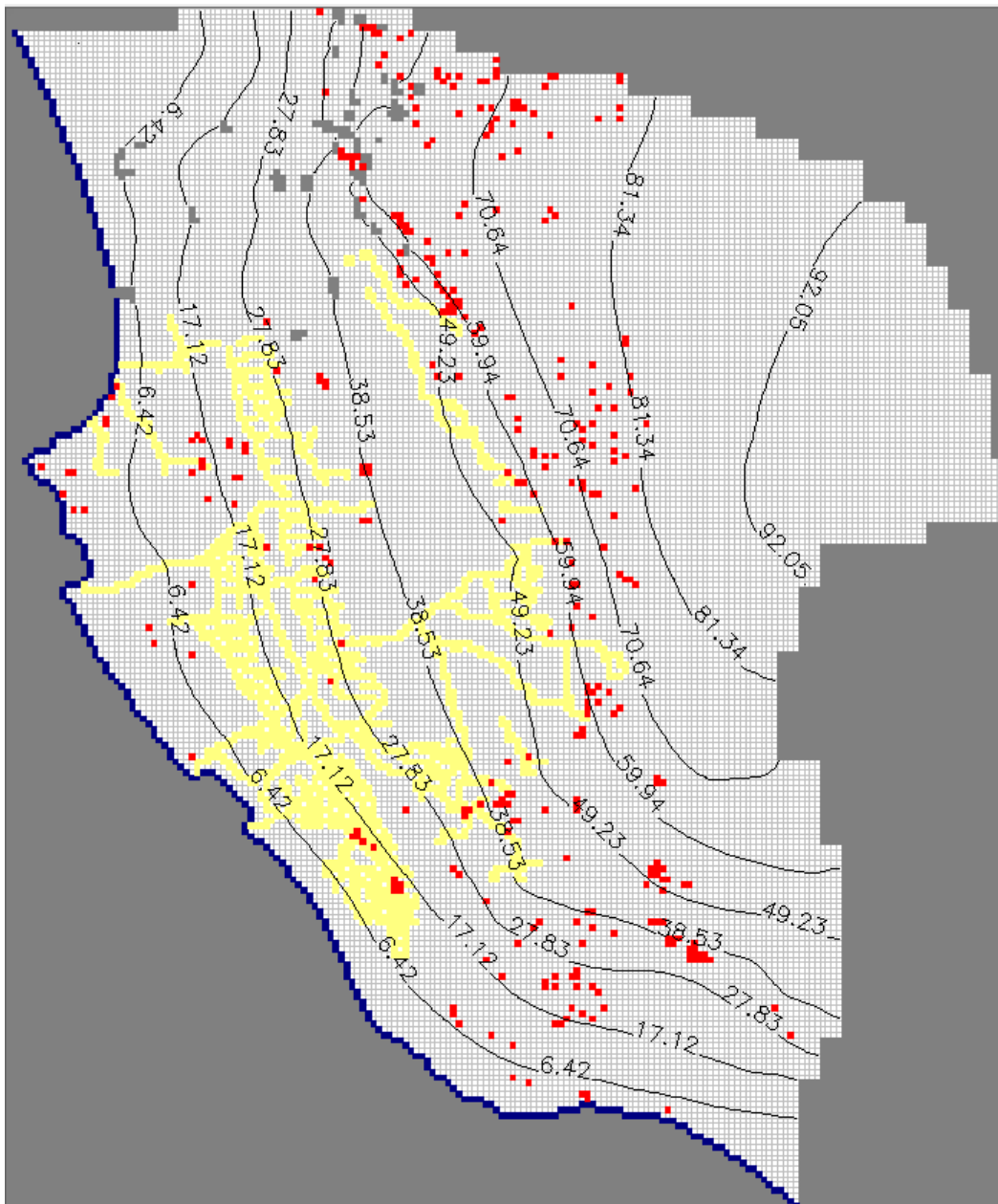


Figure 22 Groundwater head output from the layer 1 of the regional South-East model from Morgan et al. (2015).

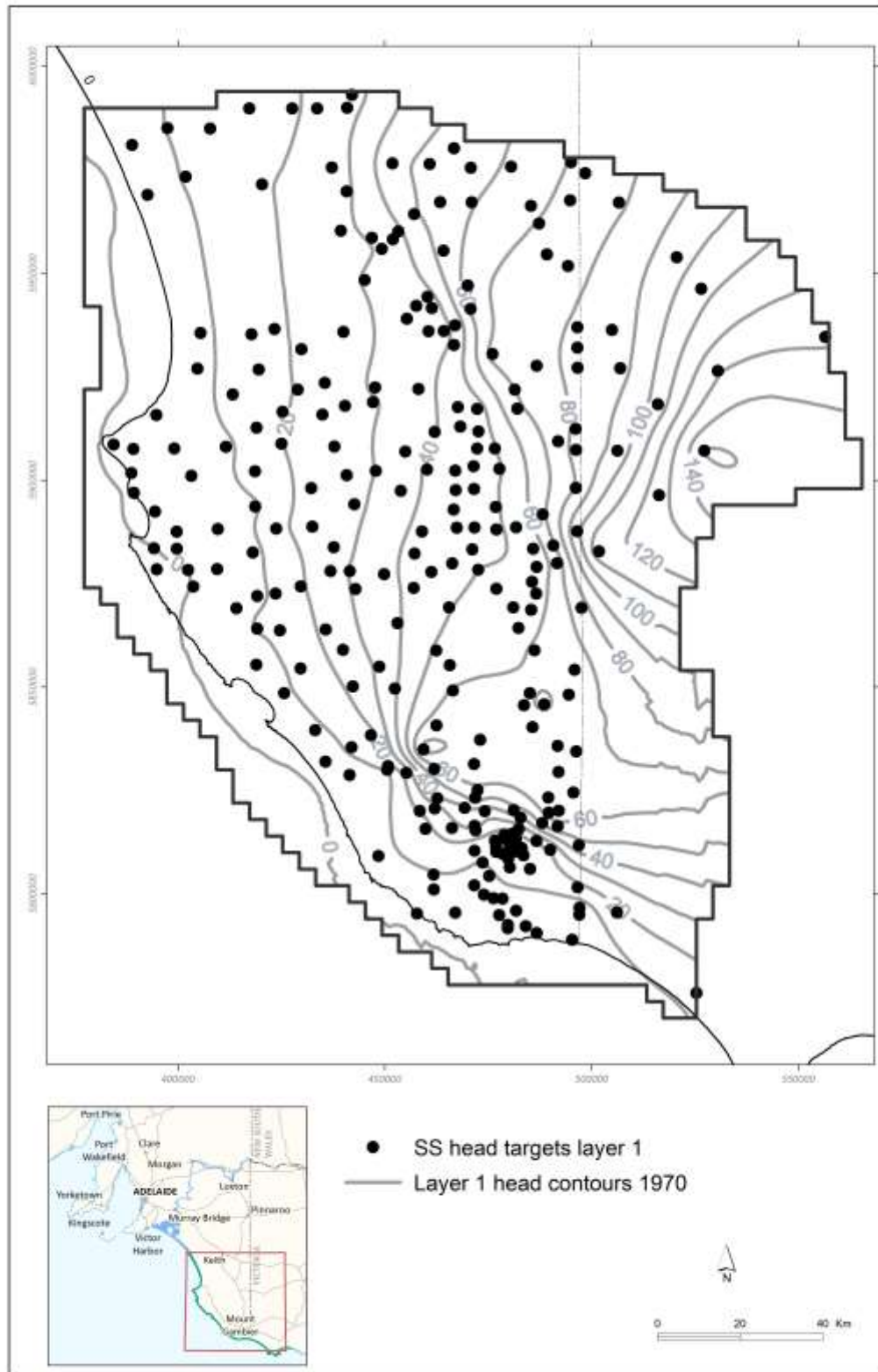


Figure 23 Steady state target heads in Layer 1 (Morgan et al. 2015)

## 4 Discussion

The research presented in this report is a proof of concept, and indicates that a net recharge – depth to water table (DTWT) lookup table is a plausible method to calculate recharge and evapotranspiration (ET) fluxes in a regional groundwater model. Using the approach in a transient groundwater model is the next step in testing its performance, particularly for estimating the impacts of climate variation, climate change and land use effects on groundwater recharge and evapotranspiration.

The benefit of this method is a more flexible and conceptually more appropriate representation of evapotranspiration and recharge under shallow groundwater conditions. The model was robust and converged under the same conditions as the regional model run with EVT and RCH packages.

Emerging patterns from the net recharge – DTWT curves were:

1. Vegetation influenced the net recharge – DTWT curves from around 0.5 to 1 m DTWT, down to a combination of plant rooting depth and capillary fringe, which was a function of soil type. For forestry land uses, this was around seven or eight metres, for crops, pasture and native vegetation this ranged between two metres and four metres.
2. For DTWT above 0.5 to 1 m, anoxic conditions led to reduction or cessation of plant transpiration.
3. Soil driven processes such as evaporation influenced the net recharge - DTWT curves from the soil surface to a depth of between one and three metres. The influence was shallow for sandy soils, and deeper for soils with higher clay proportions.
4. Rejected infiltration expressed as runoff only occurred when the DTWT was in the top metre of the soil profile.
5. Generally the curves showed net ET above two to four metres DTWT, and net recharge below this.

Several sources of uncertainty became obvious during this process of modelling recharge and ET in the South East. These include:

1. The soil, climate and vegetation parameters used to generate the WAVES curves;
2. The MODIS reflectance data used to estimate net recharge;
3. Assumptions within the CMRSET methodology of calculating ET from remotely sensed reflectance data and the water balance methodology for calculating net recharge from remotely sensed ET;
4. The land use and soils maps used to develop the landscape key;
5. The depth to watertable rasters used to calculate net recharge from the WAVES lookup table functions and lack of salinity information; and
6. Assumptions, conceptual models and parameterisation of the regional MODFLOW model.

The parameters used in the WAVES model were adapted from standard applications of WAVES, with several modifications to mimic the net recharge – DTWT relationships found in Phase 1 of the project (Crosbie and Davies 2013). One major alteration was to limit tree rooting depth to 1.5 times the depth to watertable in order to prevent tree death over very shallow groundwater. This is consistent with the behaviour of riparian vegetation and vegetation growing over seasonally shallow groundwater.

Both the ET and recharge fluxes appear to be too high in this demonstration of the WAVES/MODFLOW approach, especially for forestry and native vegetation. This is despite the cropping and pasture curves having similar maximum recharge and ET rates found in other literature for the region. In this case they tend to balance out across the region, but may produce too high or low fluxes in more local areas of the study site. This is of particular concern where soils are shallow, such as south of Mount Gambier. If this approach to modelling recharge and ET was pursued, it is advisable to perform a more rigorous calibration of WAVES parameters. This would be possible with either a number of accurate groundwater surfaces and temporally matching climate information, as an integrated calibration of WAVES and MODFLOW, linked with the R script in Appendix C, using PEST.

There may be some requirement for further upscaling the local scale ET and recharge rates from the point scale which match well with measurements from literature, to a regional scale, which encompasses many different point scale recharge and ET rates within one model cell. A probabilistic approach to defining the ET surface may be useful to account for the large range between the highest and lowest DEM elevations in each model cell.

MODIS reflectance data can be influenced by highly reflectant surfaces such as lake surfaces and salt flats. This can skew estimates of evapotranspiration and therefore net recharge estimates (Guerschman et al. 2009). Phase 1 of the project focused on bias correction of the data at a regional scale, but uncertainty is higher for spatial patterns and point scale values of net recharge.

Some of the assumptions associated with the CMRSET water balance method are in contrast with those used in the WAVES/MODFLOW modelling approach. In irrigated areas, recharge irrigation application was included in the net recharge – DTWT curves at a rate of 100 mm/year of deep drainage. This resulted in high recharge rates under irrigated areas. This may be balanced in the MODFLOW model by pumping from bores for irrigation purposes, which was modelled separately. In contrast, the CMRSET water balance method assumed higher rates of ET in irrigated areas based on the simple water balance equation used ( $R = P - ET$ ), where R is recharge, P is precipitation and ET is evapotranspiration. This inherently assumes that any applied irrigation is exactly equal to the volume pumped from the aquifer, the net result being zero. Without additional information about irrigation application volumes and leaching fractions, this is the best approximation of recharge at this scale, but due to these assumptions, it will not be equal to that calculated by WAVES-MODFLOW.

Another source of uncertainty is the land use and soil maps used in the analysis. While land use maps are generally ground truthed, geographers generally accept that they still contain some inaccuracies. Similarly the large scale of soil maps may lead to inaccuracies associated with upscaling, and do not account for multi-layered soil profiles. It may be worth doing some ground truthing of these data for improved recharge estimation, and testing the effects of duplex soils on the net recharge – DTWT curves.

Depth dependence of ET or net recharge was critical to achieve a realistic piezometric surface. The depth dependent net recharge in the WAVES-MODFLOW model allowed diffuse discharge to occur across the lowland parts of the catchment, which lowered the watertable enough to provide reasonable (though untested) volumes of drain discharge. It also facilitated a stronger break of slope in the piezometric surface along the Kanawinka fault (Figure 21, Figure 4).

Both ET and net R were sensitive to depth to groundwater using the WAVES-MODFLOW method. It is therefore very important to get an accurate measure of depth to groundwater in order to model recharge and ET processes. There was some question about the accuracy of the composite depth to groundwater data, which from both recharge modelling approaches appeared to be too high in the low-lying areas of the region, in many cases above the ground surface. It may be valuable to invest some effort into validating groundwater elevation near and within lakes, wetlands and salt flats. Constraining depth to watertable with photographic or Google Earth based evidence of salt pans or salt tolerant plants such as samphire may assist with this validation.

Similarly to the EVT or ETS packages, there may be cases of non-uniqueness associated with net recharge and groundwater depth, with errors in one data set offsetting errors in the other. Some effort to validate groundwater heads using field measurements is recommended to maximise accuracy in model predictions.

While some further work is required to calibrate the WAVES parameters, the net recharge - DTWT curves generated in WAVES reflect those appearing in other literature (Figure 24), with similar depth dependence. Soil based impacts are generally evident where the watertable is within one to two metres of the surface, while vegetation based impacts on net recharge are evident with watertables within one to six metres (depending on root distribution) of the surface.

Future development of the model would consist of further calibration of the net recharge curves produced by the WAVES model and transitioning the methodology into a temporal version of the South East regional model. It may be possible to calibrate net recharge parameters simultaneously with the steady state model using PEST. This could be done by coupling WAVES and MODFLOW with some of the R code that has

already been developed. Alternatively, it could be done more simply by converting the net recharge curves into simple two or three parameter functions and writing code to translate these functions into a MODFLOW input file format.

Applying the methodology to a temporal version of the regional model would require partitioning of the WAVES net recharge curves into seasonal or monthly averages (for stochastic approaches) or actual seasonal or monthly rates (for a historical approach) and generating one lookup table and one landscape key for each stress period.

A parallel effort to assess the local scale accuracy and uncertainty of the CMRSET data would also be useful.

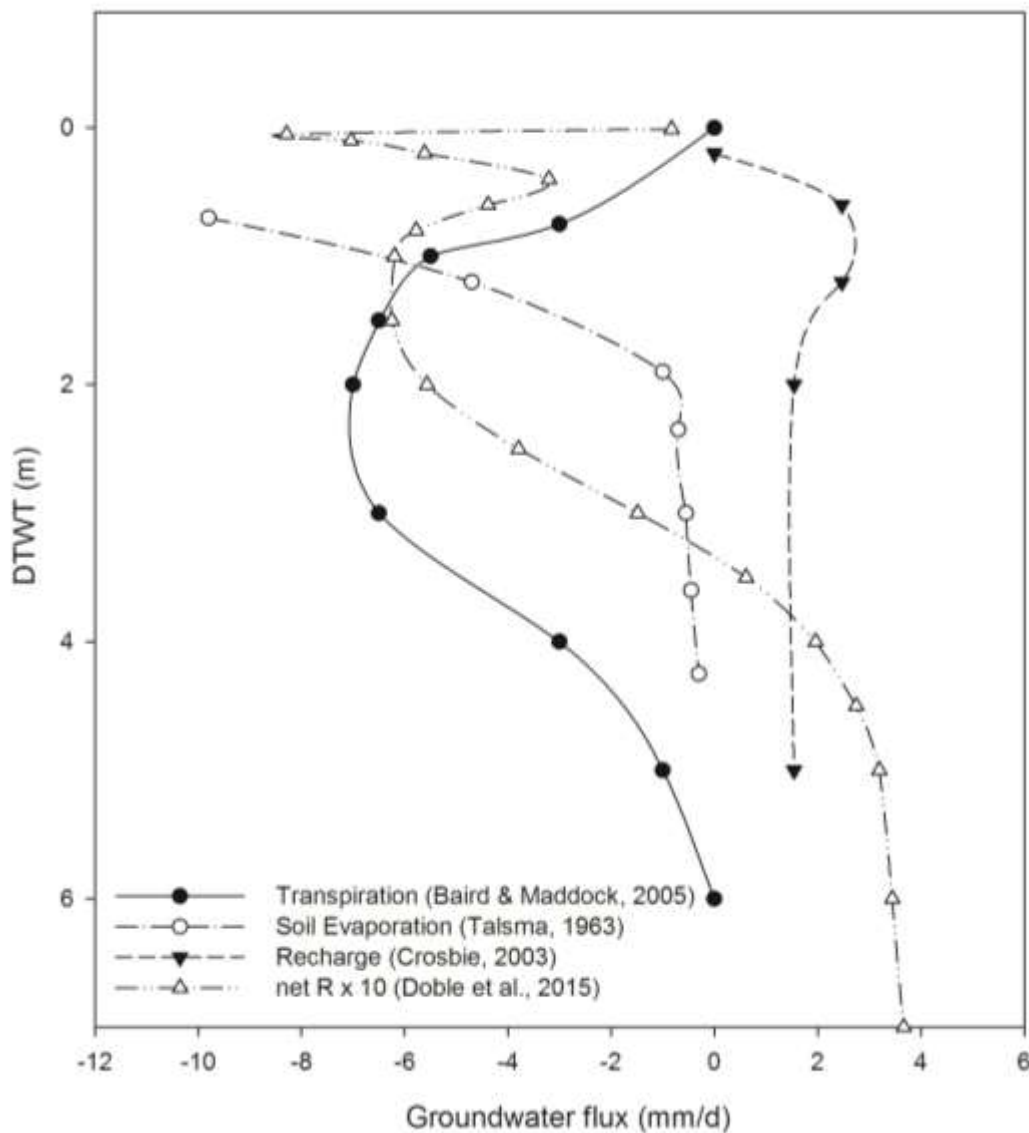


Figure 24 Groundwater flux vs. DTGW curves for transpiration of riparian vegetation in Arizona, (Baird and Maddock III 2005; Baird et al. 2005), evaporation from a fine sandy loam, California (Talsma 1963), recharge to a sandy aquifer in the Tomago Sandbeds, NSW, Australia (Crosbie 2003) and an example of net recharge from this report (multiplied by 10 for clarity).

## 5 Conclusions

The proof of concept research described in this report demonstrated the application of realistic net recharge (recharge minus evapotranspiration) functions within MODFLOW with the use of a lookup table. Relationships between depth to watertable and net recharge were developed using the SVAT model WAVES with twelve climate zones, seven soil types, eight land use types and 27 depths to the water table. These relationships were configured into a lookup table and a unique identifier landscape key was constructed for the MODFLOW model from a combination of climate, soil and vegetation type. The MODFLOW EVT package was modified to call a value of net recharge from the lookup table according to each cell's landscape key. The new MODFLOW module linearly interpolated the net recharge according to the depth to groundwater in the cell.

The process of solving iteratively for head and net recharge using this method was robust and for this example, there were no problem associated with model convergence.

Like the EVT or ETS packages, the net recharge package, NETR, is sensitive to the depth to groundwater. Therefore, some effort to validate groundwater heads using field measurements is recommended to maximise accuracy in model predictions. The net recharge – DTWT curves developed using the WAVES model had similar characteristics to evaporation, transpiration and both gross and net recharge – DTWT curves found in literature. The magnitudes of recharge, evaporation and transpiration for softwoods and hardwoods were higher than those suggested by forestry research papers.

The DTWT - net recharge curves had a similar shape and magnitude to those of the CMRSET data in the Phase 1 project report. Testing the net recharge curves with a static watertable produced similar results to recharge estimated by the MODIS/CMRSET data, but with both recharge and evapotranspiration higher than the remotely sensed net recharge, particularly in the dunal systems around Kingston SE and Lucindale. Further calibration of vegetation and soil parameters is required. With the addition of a number of programming scripts, both the net recharge functions and the MODFLOW model could be calibrated using an automated method such as PEST.



# References

- ABARE-BRS. 2010. Catchment Scale Land Use Mapping for Australia – Update March 2010. Australian Bureau of Agricultural and Resource Economics – Bureau of Rural Sciences.
- Allison, G.B., and M.W. Hughes. 1978. The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. *Australian Journal of Soil Research* 16: 181-195.
- Anderson, V.G. 1945. Some effects of atmospheric evaporation and transpiration on the composition of natural water in Australia (continued). 4. Underground waters in riverless areas. *J. Aust. Chem. Inst* 12: 83-98.
- Baird, K., J. Stromberg, and T. Maddock. 2005. Linking Riparian Dynamics and Groundwater: An Ecohydrologic Approach to Modeling Groundwater and Riparian Vegetation. *Environmental Management* 36 no. 4: 551-564.
- Baird, K.J., and T. Maddock III. 2005. Simulating riparian evapotranspiration: a new methodology and application for groundwater models. *Journal of Hydrology* 312 no. 1-4: 176-190.
- Banta, E.R. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model-documentation of packages for simulating evapotranspiration with a segmented function (ETS1) and drains with return flow (DRT1).
- Benyon, R.G., S. Theiveyanathan, and T.M. Doody. 2006. Impacts of tree plantations on groundwater in south-eastern Australia. *Australian Journal of Botany* 54 no. 2: 181-192.
- Broadbridge, P., and I. White. 1998. Constant rate rainfall infiltration: A versatile non-linear model: I. Analytical solution. *Water Resources Research* 24: 145-154.
- Brunner, P., and C.T. Simmons. 2011. HydroGeoSphere: A Fully Integrated, Physically Based Hydrological Model. *Ground Water* 50 no. 2: 170-176.
- Carsel, R.F., and R.S. Parrish. 1988. Developing joint probability distributions of soil water retention characteristics. *Water Resources Research* 24 no. 5: 755-769.
- Crosbie, R., P. Davies, N. Harrington, and S. Lamontagne. 2015. Ground truthing groundwater-recharge estimates derived from remotely sensed evapotranspiration: a case in South Australia. *Hydrogeology Journal* 23 no. 2: 335-350.
- Crosbie, R., T. Pickett, F. Mpelasoka, G. Hodgson, S. Charles, and O. Barron. 2013a. An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. *Climatic Change* 117: 41-53.
- Crosbie, R.S. 2003. The Regional Scaling of Groundwater Recharge. PhD Thesis, School of Engineering, University of Newcastle, Callaghan, NSW, Australia.
- Crosbie, R.S., and P. Davies. 2013. Recharge estimation. In: Harrington, N., Lamontagne, S. (Eds.), Framework for a regional water balance model for the South Australian Limestone Coast region. Goyder Institute for Water Research, Adelaide.
- Crosbie, R.S., B.R. Scanlon, F.S. Mpelasoka, R.C. Reedy, J.B. Gates, and L. Zhang. 2013b. Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. *Water Resources Research* 49 no. 7: 3936-3951.
- Crosbie, R.S., B. Wilson, J.D. Hughes, C. McCulloch, and W.M. King. 2008. A comparison of the water use of tree belts and pasture in recharge and discharge zones in a saline catchment in the Central West of NSW, Australia. *Agricultural Water Management* 95 no. 3: 211-223.
- Dawes, W., L. Zhang, and P. Dyce. 2004. WAVES v3.5 User Manual. CSIRO Land and Water 30.
- Dawes, W.R., M. Gilfedder, M. Stauffacher, J. Coram, S. Hajkiewicz, G.R. Walker, and M. Young. 2002. Assessing the viability of recharge reduction for dryland salinity control: Wanilla, Eyre Peninsula. *Australian Journal of Soil Research* 40 no. 8: 1407-1424.
- Doble, R., C. Simmons, I. Jolly, and G. Walker. 2006. Spatial relationships between vegetation cover and irrigation-induced groundwater discharge on a semi-arid floodplain, Australia. *Journal of Hydrology* 329 no. 1-2: 75-97.
- Doherty, J. 2005. PEST: Model Independent Parameter Estimation. fifth edition of user manual. Watermark Numerical Computing, Brisbane, Australia.
- Gardner, W.R., and M. Fireman. 1958. Laboratory studies of evaporation from soil columns in the presence of a water table. *Soil Science* 85: 244-249.

- Guerschman, J.P., A.I.J.M. Van Dijk, G. Mattersdorf, J. Beringer, L.B. Hutley, R. Leuning, R.C. Pipunic, and B.S. Sherman. 2009. Scaling of potential evapotranspiration with MODIS data reproduces flux observations and catchment water balance observations across Australia. *Journal of Hydrology* 369 no. 1-2: 107-119.
- Harbaugh, A. 2005. MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process. .
- Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, the US Geological Survey modular ground-water model - User guide to modularization concepts and the ground-water flow process. US Geological Society.
- Harrington, N., C. Wood, and W. Yan. 2011. Lower South east Water Balance Project Phase 1 - Review of the Conceptual Model and Recommendations for a Modelling Approach. Department for Water.
- Jeffrey, S.J., J.O. Carter, K.B. Moodie, and A.R. Beswick. 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software* 16 no. 4: 309-330.
- Johnston, R.M., S.J. Barry, E. Bleys, E.N. Bui, C.J. Moran, D.A.P. Simon, P. Carlile, N.J. McKenzie, B.L. Henderson, G. Chapman, M. Imhoff, D. Maschmedt, D. Howe, C. Grose, N. Schoknecht, B. Powell, and M. Grundy. 2003. ASRIS: the database. *Australian Journal of Soil Research* 41 no. 6: 1021-1036.
- Leaney, F., S. Mustafa, and J. Lawson. 2006. Salt Accumulation And Water Balance Under Different Land use In Bakers Range Area. CSIRO Land and Water
- Maddock, T.I., and K.J. Baird. 2002. A riparian evapotranspiration package. Tucson, Arizona: Department of Hydrology and Water Resources, University of Arizona Research Laboratory for Riparian Studies.
- McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference groundwater flow model. USGS.
- Morgan, L.K., N. Harrington, A.D. Werner, J. Hutson, and J. Woods. 2015. South East Regional Water Balance Project – Phase 2, Development of a Regional Groundwater Flow Model.
- Mustafa, S., J. Lawson, F. Leaney, and K. Osei-Bonsu. 2006. Land-use impact on water quality and quantity in the Lower South East, South Australia. Resource Allocation Division, Department of Water, Land and Biodiversity Conservation. Report DWLBC 2006/25. 238.
- Niswonger, R.G., D.E. Prudic, and R.S. Regan. 2006. Documentation of the Unsaturated-Zone Flow (UZFI) Package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6-A19, 62 p.
- Phillips, F.M. 1994. Environmental Tracers for Water Movement in Desert Soils of the American Southwest. *Soil Science Society of America Journal* 58 no. 1: 15-24.
- Richards, L.A. 1931. Capillary conduction of liquids through porous mediums. *Journal of Applied Physics* 1 no. 5: 318-333.
- Scanlon, B.R. 1991. Evaluation of moisture flux from chloride data in desert soils. *Journal of Hydrology* 128 no. 1-4: 137-156.
- Schmid, W., R.T. Hanson, T. Madodock III, and S.A. Leake. 2006. *User guide for the farm process (FMP1) for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, MODFLOW 2000*.: USGS: Reston, Virginia.
- Šimůnek, J., M. Šejna, and M.T. van Genuchten. 2011. The HYDRUS software package for simulating the two- and three-dimensional movement of water, heat and multiple solutes in variably-saturated media: Technical manual version 2.0. PC-Progress.
- Smith, M., R.G. Allen, J.L. Monteith, A. Perrier, L.S. Pereira, and A. Segeren. 1992. Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements. Food and Agriculture Organisation of the United Nations 60.
- Sophocleous, M. 1992. Groundwater recharge estimation and regionalization: the Great Bend Prairie of central Kansas and its recharge statistics. *Journal of Hydrology* 137: 113-140.
- Szilagyi, J., V.A. Zlotnik, and J. Jozsa. 2013. Net Recharge vs. Depth to Groundwater Relationship in the Platte River Valley of Nebraska, United States. *Groundwater* 51 no. 6: 945-951.
- Talsma, T. 1963. The control of saline groundwater. *Mededelingen van de Landbouwhogeschool te Wageningen Nederland* 63 no. 10: 1-68.
- Therrien, R., R.G. McLaren, E.A. Sudicky, and S.M. Panday. 2006. Hydrogeosphere—a three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport. Groundwater Simul. Group, Waterloo, Ont., Canada. 275 pp.
- Wohling, D.L., F.W. Leaney, and R.S. Crosbie. 2012. Deep drainage estimates using multiple linear regression with percent clay content and rainfall. *Hydrol. Earth Syst. Sci.* 16 no. 2: 563-572.
- Wood, W.W. 1999. Use and misuse of the chloride-mass balance method in estimating ground water recharge. *Ground Water* 37 no. 1: 2-3.
- Wu, H., E.J. Rykiel, T. Hatton, and J. Walker. 1994. An integrated rate methodology (IRM) for multi-factor growth rate modelling *Ecological Modelling* 73 no. 1-2: 97-116.

- Zhang, L., and W. Dawes. 1998a. WAVES - An integrated energy and water balance model. CSIRO Land and Water 218.
- Zhang, L., and W. Dawes. 1998b. WAVES: an integrated energy and water balance model. CSIRO Land and Water.
- Zhang, L., W.R. Dawes, and T.J. Hatton. 1996. Modelling hydrologic processes using a biophysically based model- application of WAVES to FIFE and HAPEX-MOBILHY. *Journal of Hydrology* 185 no. 1-4: 147-169.
- Zhang, L., W.R. Dawes, T.J. Hatton, I.H. Hume, M.G. O'Connell, D.C. Mitchell, P.L. Milthorp, and M. Yee. 1999a. Estimating episodic recharge under different crop/pasture rotations in the Mallee region. Part 2. Recharge control by agronomic practices. *Agricultural Water Management* 42 no. 2: 237-249.
- Zhang, L., W.R. Dawes, P.G. Slavich, W.S. Meyer, P.J. Thorburn, D.J. Smith, and G.R. Walker. 1999b. Growth and ground water uptake responses of lucerne to changes in groundwater levels and salinity: lysimeter, isotope and modelling studies. *Agricultural Water Management* 39 no. 2-3: 265-282.

## Appendix A MODFLOW NRF package

### NRF – Net Recharge Function Package

Based on the EVT Package. Uses a user defined lookup table to determine the net recharge value for the current head as defined by NEVTOP

<b>Abbreviation in Name file</b>	NRF
<b>Purpose</b>	The Net Recharge package is used to simulate a head-dependent flux out of the model distributed over the top of the model and specified in units of length/time. Within MODFLOW, these rates are multiplied by the horizontal area of the cells to which they are applied to calculate the volumetric flux rates.
<b>Documentation</b>	•Doble, R.C, Pickett, T., Crosbie, R.S., Morgan, L., 2015, <i>A new approach for modelling groundwater recharge in the South East of South Australia using MODFLOW</i> , Goyder Institute for Water Research Technical Report 15/X.
<b>Related Packages</b>	<a href="#">Head-Dependent Flux Boundary packages</a>
<b>Supported in</b>	• MODFLOW-2000-NETR
<b>Common Errors</b>	.
<b>Other Notes</b>	•

### Input Instructions

Input to the Net Recharge (NRF) Package is read from the file that is type " NRF " in the [name](#) file. All single-valued variables are free format if the option "FREE" is specified in the Basic Package input file; otherwise, the variables have 10-character fields.

FOR EACH SIMULATION	
<b>Data Set 0</b>	[#Text] Item 0 is optional—"#" must be in column 1. Item 0 can be repeated multiple times. <a href="#">Text</a> Text—is a character variable (199 characters) that starts in column 2. Any characters can be included in Text. The "#" character must be in column 1. Except for the name file, lines beginning with # are restricted to these first lines of the file. Text is printed when the file is read.
<b>Data Set 1</b>	NRFOP INRFCB MXNNRI MXNDPTH <a href="#">Explanation of variables</a> <a href="#">NRFOP</a>

	<p>NRFOP—is the net recharge flux option code. Net Recharge Flux (NRF) is calculated for one cell in each vertical column. The option codes determine the cell within a column for which NRF will be calculated.</p> <ol style="list-style-type: none"> <li>1. NRF is calculated only for cells in the top grid layer.</li> <li>2. The cell for each vertical column is specified by the user in variable <b>INRF</b>.</li> <li>3. Net Recharge Flux is applied to the highest active cell in each vertical column</li> </ol> <p><b>INRFCB</b> INRFCB—is a flag and a unit number. If <math>INRFCB &gt; 0</math>, it is the unit number to which cell-by-cell flow terms will be written when "SAVE BUDGET" or a non-zero value for ICBCFL is specified in Output Control. If <math>INRFCB \leq 0</math>, cell-by-cell flow terms will not be written.</p> <p><b>MXNNRI</b> MXNNRI— is the maximum number of unique soil\veg\climate combination indicators that will be read for any stress period. MXNNRI+1 is the maximum number of rows in the Net Recharge Flux Lookup Table.</p> <p><b>MXNDPTH</b> MXNDPTS— is the maximum number of unique depth to water table values that will be read for any stress period. MXNDPTH is the maximum number of columns in the Net Recharge Flux Lookup Table.</p>
FOR EACH STRESS PERIOD	
Data Set 2	<p>INNRI LU INNRI LY INSURF ININD</p> <p><b>Explanation of variables</b></p> <p><b>INNRI LU</b> INNRI LU—is the Net Recharge Indicator (<b>NRI</b>) and Net Recharge Flux Look-up Table (<b>NRL</b>) read flag.</p> <p>If <math>INNRI LU \geq 0</math>, a sequential array of Net Recharge Indicators (<b>NRI</b>) and a look-up table (<b>NRL</b>) with a net recharge flux for each defined water table height and unique indicator value (<b>NRI</b>) will be read. The values in the array provide a key to rows 2 to NNRI+1 of the NRL</p> <p>If <math>INNRI LU &lt; 0</math>, the array and look-up table from the preceding stress</p> <ul style="list-style-type: none"> <li>• period will be reused.</li> </ul> <p><b>INNRI LY</b> INNRI LY—is the Net Recharge Indicator Layer (<b>NRIL</b>) read flag.</p> <p>If <math>INNRI LY \geq 0</math>, a layer variable containing the Net Recharge Indicators (<b>NRI</b>) (a layer indicating soil/veg/climate combination for each cell) will</p> <ul style="list-style-type: none"> <li>• be read.</li> </ul> <p>If <math>INNRI LY &lt; 0</math>, the Net Recharge Indicators from the preceding stress</p> <ul style="list-style-type: none"> <li>• period will be reused.</li> </ul> <p><b>INSURF</b> INSURF—is the Surface Layer (<b>SURF</b>) read flag.</p> <p>If <math>INSURF \geq 0</math>, a layer variable containing heights for each cell from</p> <ul style="list-style-type: none"> <li>• which depth to water table is measured will be read.</li> <li>• If <math>INSURF &lt; 0</math>, layer from the preceding stress period will be reused.</li> </ul> <p><b>ININD</b></p>



	<p>ININD—is the layer indicator (<b>INRF</b>) read flag. It is read only if the NRF option (<b>NRFOP</b>) is equal to two.</p> <p>If <math>ININD \geq 0</math>, a layer variable containing the layer indicators (<b>INRF</b>) will</p> <ul style="list-style-type: none"> <li>• be read.</li> </ul> <p>If <math>ININD &lt; 0</math>, layer indicators used during the preceding stress period will</p> <ul style="list-style-type: none"> <li>• be reused.</li> </ul>
<b>Data Set 3</b>	<p>NINDS NDPTHS</p> <p><b>Explanation of variables</b></p> <p><b>NINDS</b></p> <p>NINDS—— is the number of unique soil\veg\climate combination indicators that will be read for this stress period. NINDS is used to define the size of the indicator array. NINDS will only be read if <math>INNRLU \geq 0</math>. NINDS must not exceed MXNINDS.</p> <p><b>NDPTHs</b></p> <p>NDPTHs— is the maximum number of unique depth to water table values that will be read for this stress period. NDPTHs is used define the size of the indicator array. NDPTHs will only be read if <math>INNRLU \geq 0</math>.NDPTHs must not exceed MXNDPTHs.</p>
<b>Data Set 4</b>	<p>[NRI(NINDS)] -- <b>U2DINT</b> If <math>INNRLU \geq 0</math></p> <p><b>NRI</b></p> <p>NRI—is the soil\veg\climate combination indicator. One indicator is used for each combination. This variable must map to rows 2 - NINDS+1 of NRL so that row n+1 of the NRL contains heights for NRI(n). This variable is read only if <math>INNRLU \geq 0</math> NRI values must be integers <math>&gt; 0</math>.</p>
<b>Data Set 5</b>	<p>[NRL(NDPTHs,NINDS+1)] -- <b>U2DREL</b> If <math>INNRLU \geq 0</math></p> <p><b>NRL</b></p> <p>NRL—is structured thus:</p> <p>Row 1 contains each of the (unique) depth to groundwater values (DPTH) in ascending order</p> <p>Rows 2 to NINDS+1 contains net recharge flux values for each NRI, DPTH combination. Thus cell(i,j) contains the net recharge flux value for NRI(j-1) and DPTH(i).</p>
<b>Data Set 6</b>	<p>[INRIL(NCOL,NROW)] -- <b>U2DINT</b> If <math>INNRLY \geq 0</math></p> <p><b>NRIL</b></p> <p>NRIL—is a layer containing a NRI value for each cell. If the NRI value <math>&gt; 0</math> then a net recharge flux for this cell is calculated using the NRL and current depth to groundwater. If NRI value = 0, the cell is ignored. NRIL is read only if <math>INNRLY \geq 0</math>.</p>
<b>Data Set 7</b>	<p>[NSURF(NCOL,NROW)] -- <b>U2DREL</b> If <math>INSURF \geq 0</math></p> <p><b>SURF</b></p>

	SURF—a global height indicating the elevation from which depth to water table is measured. Read only if <b>INSURF</b> $\geq 0$ .
<b>Data Set 8</b>	<p>[IND(NCOL,NROW)] -- <b>U2DINT</b> If <b>NRFOP</b> =2 and <b>ININD</b> <math>\geq 0</math></p> <p><b>IND</b></p> <p>IND—is the layer indicator variable. For each horizontal location, it indicates the layer where net recharge is applied. It is only read if <b>NRFOP</b> =2 and <b>ININD</b> <math>\geq 0</math>.</p> <p>If <b>NRFOP</b> =2 and <b>ININD</b> <math>&lt; 0</math> IND from the previous stress period is used.</p>

## Appendix B MODFLOW lookup table

Column 1 (DTW) represents the lookup key, and the header row indicates the depth to water table at which the net recharge is applicable. The net recharge – DTWT curve for each landscape key is represented by a row of data.

DTW	0	0.01	0.05	0.1	0.2	0.4	0.6	0.8	1	1.5	.....	16	18	20
111	315.68	315.68	315.4	314.33	309.5	304.75	300.94	268.32	236.54	257.18		321.02	321.02	321.01
121	315.49	315.49	314.98	313.59	310.36	321.35	324.81	285.82	247.63	265.45		316.93	316.92	316.92
131	315.46	315.46	314.74	313.43	308.27	288.95	237.5	172.17	143.99	184.98		300.3	300.29	300.28
141	315.42	315.42	314.96	313.75	308.98	290.45	244.47	165.9	95.77	76.04		275.52	275.5	275.48
151	278.83	278.83	278.25	277.08	273.42	258.34	221.45	151.98	78.15	27.34		235.15	235.13	235.1
161	278.66	278.66	278.07	277.19	274.42	263.24	239.78	193.87	131.47	27.91		203.43	203.48	203.52
171	279.62	279.62	279.27	278.71	277.23	271.97	261.61	244.36	218.79	125.35		148.32	151.42	153.64
112	318.09	318.09	318.11	317.75	300.37	56.54	-71.49	-105.02	-87.97	78.49		243.66	243.66	243.62
122	317.99	317.99	317.67	318	309.33	18.09	-101.83	-116.12	-75.4	105.71		239.9	239.87	239.82
132	317.79	317.79	318.04	317.83	309.78	16.23	-121.01	-167.91	-166.75	-54.17		227.06	227.07	226.99
142	318.16	318.16	317.85	317.61	301.14	43.79	-103.56	-165.78	-189.02	-171.36		203.88	203.86	203.78
152	281.69	281.69	281.01	280	275.19	24.91	-114.23	-179.94	-208.85	-210.34		165.21	165.28	165.25
162	279.22	279.22	282.38	284	263.08	76.04	-59.52	-136.68	-181.98	-214.66		131.1	131.39	131.66
172	287.69	287.69	287.55	281.95	265.86	187.32	66.13	-21.41	-84.45	-178.28		76.89	82.89	87.17
113	318.09	318.09	318.11	317.75	317.79	317.25	228.1	-26.68	-56.08	-41.09		191.24	191.24	191.21
123	317.99	317.99	317.67	318.03	319.79	326.27	202.71	-37.63	-61.46	-18.28		185.85	185.83	185.81

133	317.79	317.79	318.05	318.09	318.02	274.25	179.43	-56.38	-107.59	-124.5	174.79	174.77	174.73
143	318.16	318.16	317.85	318.19	317.97	271.44	181.6	-48.77	-112.98	-166.77	154.02	154.09	154.14
153	281.71	281.71	281.95	281.78	281.8	246.09	168.6	-63.21	-137.27	-203.52	108.59	109	109.27
163	282.2	282.2	282.19	281.88	282.14	249.68	198.06	-26.07	-119.16	-206.48	74.24	75.42	76.25
173	283.32	283.32	283.4	283.32	282.61	266.03	194.16	80.44	-41.35	-202.51	26.46	36.46	43.62
114	318.09	318.09	318.06	315.79	214.61	-30.41	-108.67	-131.83	-136.16	-100.04	124.89	123.03	125.9
124	317.89	317.89	317.26	310.2	162.52	-61.83	-144.96	-178.15	-164.84	-101.3	118.67	120.2	119.33
134	317.12	317.12	317.15	308.88	178.43	-75.29	-189.92	-231.95	-240.35	-198.52	105.49	107.25	105
144	317.65	317.65	317.34	312.2	217.92	-39.96	-178.29	-242.6	-270.06	-276.93	81.11	82.53	82.01
154	272.54	272.54	276.83	262.56	158.57	-84.12	-223.86	-293.15	-324.22	-343.28	45.55	49.35	49.94
164	267.86	267.86	275.45	262.51	191.3	-27.39	-179.52	-268.59	-314.21	-358.99	25.11	28.15	30.43
174	267.09	267.09	277.5	268.7	233.53	85.08	-75.87	-192.59	-268.1	-369.48	-47.18	-28.88	-15.64
115	415.68	415.68	415.4	414.33	409.5	404.75	400.94	368.32	336.54	357.18	421.02	421.02	421.01
125	415.49	415.49	414.98	413.59	410.36	421.35	424.81	385.82	347.63	365.45	416.93	416.92	416.92
135	415.46	415.46	414.74	413.43	408.27	388.95	337.5	272.17	243.99	284.98	400.3	400.29	400.28
145	415.42	415.42	414.96	413.75	408.98	390.45	344.47	265.9	195.77	176.04	375.52	375.5	375.48
155	378.83	378.83	378.25	377.08	373.42	358.34	321.45	251.98	178.15	127.34	335.15	335.13	335.1
165	378.66	378.66	378.07	377.19	374.42	363.24	339.78	293.87	231.47	127.91	303.43	303.48	303.52
175	379.62	379.62	379.27	378.71	377.23	371.97	361.61	344.36	318.79	225.35	248.32	251.42	253.64
116	318.09	318.09	318.06	315.79	214.61	-30.41	-108.67	-131.83	-136.16	-100.04	124.89	123.03	125.9
126	317.89	317.89	317.26	310.2	162.52	-61.83	-144.96	-178.15	-164.84	-101.3	118.67	120.2	119.33
136	317.12	317.12	317.15	308.88	178.43	-75.29	-189.92	-231.95	-240.35	-198.52	105.49	107.25	105
146	317.65	317.65	317.34	312.2	217.92	-39.96	-178.29	-242.6	-270.06	-276.93	81.11	82.53	82.01

156	272.54	272.54	276.83	262.56	158.57	-84.12	-223.86	-293.15	-324.22	-343.28	45.55	49.35	49.94
166	267.86	267.86	275.45	262.51	191.3	-27.39	-179.52	-268.59	-314.21	-358.99	25.11	28.15	30.43
176	267.09	267.09	277.5	268.7	233.53	85.08	-75.87	-192.59	-268.1	-369.48	-47.18	-28.88	-15.64
118	315.68	315.68	315.4	314.33	309.5	304.75	300.94	268.32	236.54	257.18	321.02	321.02	321.01
128	315.49	315.49	314.98	313.59	310.36	321.35	324.81	285.82	247.63	265.45	316.93	316.92	316.92
138	315.46	315.46	314.74	313.43	308.27	288.95	237.5	172.17	143.99	184.98	300.3	300.29	300.28
148	315.42	315.42	314.96	313.75	308.98	290.45	244.47	165.9	95.77	76.04	275.52	275.5	275.48
158	278.83	278.83	278.25	277.08	273.42	258.34	221.45	151.98	78.15	27.34	235.15	235.13	235.1
168	278.66	278.66	278.07	277.19	274.42	263.24	239.78	193.87	131.47	27.91	203.43	203.48	203.52
178	279.62	279.62	279.27	278.71	277.23	271.97	261.61	244.36	218.79	125.35	148.32	151.42	153.64
119	315.68	315.68	315.4	314.33	309.5	304.75	300.94	268.32	236.54	257.18	321.02	321.02	321.01
129	315.49	315.49	314.98	313.59	310.36	321.35	324.81	285.82	247.63	265.45	316.93	316.92	316.92
139	315.46	315.46	314.74	313.43	308.27	288.95	237.5	172.17	143.99	184.98	300.3	300.29	300.28
149	315.42	315.42	314.96	313.75	308.98	290.45	244.47	165.9	95.77	76.04	275.52	275.5	275.48
159	278.83	278.83	278.25	277.08	273.42	258.34	221.45	151.98	78.15	27.34	235.15	235.13	235.1
169	278.66	278.66	278.07	277.19	274.42	263.24	239.78	193.87	131.47	27.91	203.43	203.48	203.52
179	279.62	279.62	279.27	278.71	277.23	271.97	261.61	244.36	218.79	125.35	148.32	151.42	153.64

Only first climate zone shown



# Appendix C Code for processing WAVES outputs

## C.1 R code to read in WAVES outputs and write out as a file for MODFLOW

```
# Goyder South East
# Climate files set up
# Rebecca Doble
# CSIRO
#
# Load all required packages
#
library(sp)
library(zoo)
library(xts)
library(spacetime)
library(gstat)
library(ggplot2)
#
#
##### How to do this

# Run WAVES for each of the climate, soil vegetation scenarios
# The results will be automatically read in
# This code will write out the MODFLOW file for the lookup table
# Then run WAVES_CMSETcalib4.R (or later version) to compare the results using a static watertable with
the CMRSET output.

#####write out as a file for MODFLOW#####

fileTagList <- c("Beachport","Bordertown","CapeNorth","Dartmoor","Edenhope",
               "Goroke","Kingston","Lucindale","MtBurr","MtGamb","Naracoorte","Penola")
fileTagList <- c("Beach","BT","CapeN","Dart","Eden",
               "Goroke","Kingston","Lucindale","MtBurr","MtG","Naracoorte","Penola")

#i <- "Dart" # make this loop later on.
fpathOut <- "Z:/Goyder/WAVES/RussellCalib/"
#fpathOut <- "X:/work/RRF/Goyder_SE/WAVES/Feb15_2/"

yAxis <- array(c(0.01, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18,
20),dim=c(1,26)) #26
yAxisMF <- array(c(0.0, 0.01, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 10, 12, 14,
16, 18, 20),dim=c(1,27)) #26
lookup <- data.frame(yAxisMF, row.names="DTW")
```

```

for (i in fileTagList) {

  #fpath <- "//wron/working/work/doble/Goyder/WAVES/WAVESoutputs/"
  #fpath <- "//wron/working/work/doble/Goyder/WAVES/Nov_14_runs/"
  #fpath <- "Z:/Goyder/WAVES/WAVESNov14/"
  fpath <- "Z:/Goyder/WAVES/RussellCalib/"
  #fpath <- "Z:/Goyder/WAVES/WAVESFeb15/"
  #fpath <- paste("X:/work/RRF/Goyder_SE/WAVES/Feb15_2/",i,"/",sep="")

  summaryTable <- read.table(file=paste(fpath,"summary",i,".txt",sep=""), header = TRUE)

  ItaTable <- read.table(file=paste(fpath,"100yr_ave",i,".txt",sep=""), header = TRUE)

  summaryTable["net_R"] <- NA
  summaryTable["OS_T"] <- NA
  summaryTable["US_T"] <- NA
  summaryTable["LAI_O"] <- NA
  summaryTable["LAI_U"] <- NA
  summaryTable["Soil_E"] <- NA
  summaryTable["Q"] <- NA
  summaryTable["OS_i"] <- NA
  summaryTable["US_i"] <- NA
  summaryTable["Gross_R"] <- NA

  ff <- 1 # this is the percentage of runoff that becomes recharge after hitting depressions
  # make sure you change this in ClimateSetUp5.r too

  summaryTable$net_R <- ItaTable$net_R -ff*ItaTable$Q
  summaryTable$OS_T <- ItaTable$OS_T
  summaryTable$US_T <- ItaTable$US_T
  summaryTable$LAI_O <- ItaTable$LAI_O
  summaryTable$LAI_U <- ItaTable$LAI_U
  summaryTable$Soil_E <- ItaTable$Soil_E
  summaryTable$Q <- (1-ff)*ItaTable$Q
  summaryTable$OS_i <- ItaTable$OS_i
  summaryTable$US_i <- ItaTable$US_i
  summaryTable$Gross_R <- ItaTable$Gross_R -ff*ItaTable$Q

  climateList <- summaryTable$climate
  climateList <- gsub(".clm","",climateList)
  depthList <- gsub("^[^0-9]", "", climateList)
  depthListUnique <- unique(depthList)
  climateList <- gsub("[0-9]", "", climateList)
  climateListUnique <- unique(climateList)
  soilList <- gsub(".tab","",summaryTable$Soil)
  soilListUnique <- unique(gsub(".tab","",summaryTable$Soil))
  vegList <- gsub(".veg","",summaryTable$Veg)
  vegListUnique <- unique(gsub(".veg","",summaryTable$Veg))

  combList <- expand.grid(climateListUnique,soilListUnique,vegListUnique)

  combList$Var4 <- do.call(paste, c(combList[c("Var1", "Var2", "Var3")], sep = "_"))
  #summaryTable$index <- c(climateList, soilList, vegList, sep = "")

```

```

summaryTable$clim <- gsub("[0-9]", "", summaryTable$climate)
summaryTable$index <- do.call(paste, c(summaryTable[c("clim", "Soil", "Veg")], sep = " _"))
summaryTable$depth <- gsub("[^0-9]", "", summaryTable$climate)
summaryTable$index <- gsub(".veg", "", summaryTable$index)
summaryTable$index <- gsub(".tab", "", summaryTable$index)
summaryTable$index <- gsub(".clm", "", summaryTable$index)
#summaryTable$index <- gsub("[0-9]", "", summaryTable$index)

xrech100 <- array(0, dim=length(depthListUnique))
xrech50 <- array(0, dim=length(depthListUnique))

test <- array(0, dim=length(depthListUnique))
# yAxis <- array(as.numeric(summaryTable$depth[which(summaryTable$index == x)])/(-100), dim =
c(1, length(depthListUnique)))

#depthListWrite <- array(depthList, dim=c(1,28))
netRdf <- data.frame(yAxis, row.names="DTW")

for (x in combList$Var4) {
  count <- which(combList$Var4 == x)
  # graphTitle <- x
  typeList <- which(summaryTable$index == x)

  # if (length(intersect(pointer, lineNumsVeg)) > 0) {

    #for (y in length(depthListUnique)) {
  # for (y in typeList) {

    xnet_R <- array(summaryTable$net_R[typeList], dim = length(typeList))

    # as depth expressed as cm in file, to make into metres and positive
  # newRow <- array(xnet_R, dim=c(1,26))
  # newRow <- data.frame(newRow, row.names=x)
  # netRdf <- rbind(netRdf, newRow)
  # }

  # compile into matrix and write out as text file
  newRow <- array(xnet_R, dim=c(1,26))
  newRow <- data.frame(newRow, row.names=x)
  netRdf <- rbind(netRdf, newRow)
  # }

}

write.table(netRdf, file=paste(fpathOut, "MODFLOW_", i, "2.txt", sep=""), row.names=TRUE,
col.names=FALSE, sep=" ")

#Add the 0 metre depth values and copy the softwood values to the hardwood type.
netRdf_MF <- cbind(netRdf[,1], netRdf[,1:26])
netRdf_MF[1,1] <- 0.0

```

```

netRdf_MF <- rbind(netRdf_MF,netRdf_MF[2:8,]+100) # this copies crops + 100mm/a
netRdf_MF <- rbind(netRdf_MF,netRdf_MF[23:29,]) # this copies softwood data to hardwood
netRdf_MF <- rbind(netRdf_MF,netRdf_MF[2:8,]) # this copies crops to open water
netRdf_MF <- rbind(netRdf_MF,netRdf_MF[2:8,]) # this copies crops to 'other'

rNam <- row.names(netRdf_MF)
for (x in c(1:7)){
  loc <- 29+x
  rNam[loc] <- paste(i,"_soil",x,"_irrigation",sep="")
}
for (x in c(1:7)){
  loc <- 36+x
  rNam[loc] <- paste(i,"_soil",x,"_hardwoods",sep="")
}
for (x in c(1:7)){
  loc <- 43+x
  rNam[loc] <- paste(i,"_soil",x,"_water",sep="")
}
for (x in c(1:7)){
  loc <- 50+x
  rNam[loc] <- paste(i,"_soil",x,"_other",sep="")
}
rownames(netRdf_MF) <- rNam

colnames(netRdf_MF) <- c("X1","X2","X3","X4","X5","X6","X7","X8","X9","X10","X11","X12","X13","X14",
  "X15","X16","X17","X18","X19","X20","X21","X22","X23","X24","X25","X26","X27")
op <- options(stringsAsFactors=F) #set to F
lookup <- rbind(lookup,netRdf_MF[2:57,])

write.table(netRdf_MF, file=paste(fpathOut,"MODFLOW_",i,".txt",sep=""), row.names=TRUE,
col.names=FALSE, sep=" ")

}

#fpathcode <- "Z:/Goyder/WAVES/WAVESFeb15/"
#codetable <- read.table(file=paste(fpathcode,"MODFLOW_Code.txt",sep=""), header = TRUE)

code <- array(0,dim=12*7*8)

i <- 1

for (x in c(1:12)) {
  for (y in c(1,2,3,4,5,6,8,9)) {
    for (z in c(1:7)) {
      code[i] <- x*100+z*10+y
      i <- i+1
    }
  }
}
code2 <- c("DTW",code)

```

```
rownames(lookup) <- code2

write.table(lookup, file=paste(fpathOut,"MODFLOW_Code8vegRussellCalib.txt",sep=""), row.names=TRUE,
col.names=FALSE, sep=" ")

# This sets up the MODFLOW file with the eight different vegetation types
```

## C.2 R code for plotting netR-DTWT curves and creating boxplots

```
# Goyder South East
# Climate files set up
# Rebecca Doble
# CSIRO
#
# Load all required packages
#
library(sp)
library(zoo)
library(xts)
library(spacetime)
library(gstat)
library(ggplot2)

##### Bit to set up climate files

fpath <- "//wron/working/work/doble/Goyder/WAVES/ClimateFiles/"
#fpath <- "Z:/Goyder/WAVES/ClimateFiles/"

fileList <-
c("MtGamb.clm","Beachport.clm","BorderTown.clm","CapeNorth.clm","Dartmoor.clm","Edenhope.clm",
  "Goroke.clm","Kingston.clm","Lucindale.clm","MtBurr.clm","Naracoorte.clm","Penola.clm")

#fileList <- c("Beachport.clm","BorderTown.clm","CapeNorth.clm","Dartmoor.clm","Edenhope.clm",
# "Goroke.clm","Kingston.clm","Lucindale.clm","MtBurr.clm","Naracoorte.clm","Penola.clm")    #12
climate types

for (y in fileList){

  climateBase <- read.table(file=paste(fpath,y,sep=""), header = FALSE, sep = "\t")

  depthList <- c(0.01, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18,
20) #28
```



```

#depthChar <- as.character(depthList * 100)
location <- sub(".clm","",y)

for (x in depthList) {

  climateBase[,9] <- x
  depthChar <- as.character(x*100)
  write.table(climateBase,file=paste(fpath,location,depthChar,".clm",sep=""), sep = "\t", row.names =
FALSE, col.names = FALSE)

}
}

##### Bit to read and plot results

fileTagList <- c("Beach","BT","CapeN","Dart","Eden",
  "Goroke","Kingston","Lucindale","MtBurr","MtG","Naracoorte","Penola")
fpathPlot <- "Z:/Goyder/WAVES/"

pdf(paste(fpathPlot,"CurvesPlots.pdf",sep=""),width=10, height=7)

for (c in fileTagList) {

  veg <- c("crops", "Native_Veg", "pasture", "softwoods")
  for (v in veg) {

    # change this to change the format of the plots, 4x2 or 2x2

    par(mfrow = c(2,4))
    #par(mfrow = c(2,2))

    # read in output files

    #fpath <- "//wron/working/work/doble/Goyder/WAVES/WAVESoutput/"
    #fpath <- "//wron/working/work/doble/Goyder/WAVES/WAVESRootingDepth/"
    #fpath <- "Z:/Goyder/WAVES/WAVESRootingDepth/"
    fpath <- "Z:/Goyder/WAVES/RussellCalib/"
    #fpath <- "Z:/Goyder/WAVES/WAVESFeb15/"
    #changed to folders here
    #fpathMF <- "X:/work/RRF/Goyder_SE/WAVES/Feb15_2/mtGamb/"

    # choose the climate location
    #summaryTable <- read.table(file=paste(fpath,"summaryDart.txt",sep=""), header = TRUE)
    #summaryTable <- read.table(file=paste(fpath,"summary.txt",sep=""), header = TRUE)
    #summaryTable <- read.table(file=paste(fpath,"summaryLucindale.txt",sep=""), header = TRUE)
    summaryTable <- read.table(file=paste(fpath,"summaryMtG.txt",sep=""), header = TRUE)
    #summaryTable <- read.table(file=paste(fpath,"summaryBT.txt",sep=""), header = TRUE)
    #summaryTable <- read.table(file=paste(fpathMF,"summary.txt",sep=""), header = TRUE)
    summaryTable <- read.table(file=paste(fpath,"summary",c,".txt",sep=""), header = TRUE)

    #ltaTable <- read.table(file=paste(fpath,"100yr_aveDart.txt",sep=""), header = TRUE)

```

```
#ltaTable <- read.table(file=paste(fpath,"100yr_average_recharge.txt",sep=""), header = TRUE)
#ltaTable <- read.table(file=paste(fpath,"100yr_aveLucindale.txt",sep=""), header = TRUE)
ltaTable <- read.table(file=paste(fpath,"100yr_ave",c,".txt",sep=""), header = TRUE)
#ltaTable <- read.table(file=paste(fpath,"100yr_aveBT.txt",sep=""), header = TRUE)
#ltaTable <- read.table(file=paste(fpathMF,"100yr_average_recharge.txt",sep=""), header = TRUE)
```

```
summaryTable["net_R"] <- NA
summaryTable["OS_T"] <- NA
summaryTable["US_T"] <- NA
summaryTable["LAI_O"] <- NA
summaryTable["LAI_U"] <- NA
summaryTable["Soil_E"] <- NA
summaryTable["Q"] <- NA
summaryTable["OS_i"] <- NA
summaryTable["US_i"] <- NA
summaryTable["Gross_R"] <- NA
summaryTable["ETGW"] <- NA
summaryTable["ETtot"] <- NA
```

```
ff <- 1
```

```
summaryTable$net_R <- ltaTable$net_R - ff*ltaTable$Q
summaryTable$OS_T <- ltaTable$OS_T
summaryTable$US_T <- ltaTable$US_T
summaryTable$LAI_O <- ltaTable$LAI_O
summaryTable$LAI_U <- ltaTable$LAI_U
summaryTable$Soil_E <- ltaTable$Soil_E
summaryTable$Q <- (1-ff)*ltaTable$Q
summaryTable$OS_i <- ltaTable$OS_i
summaryTable$US_i <- ltaTable$US_i
#summaryTable$Gross_R <- ltaTable$Gross_R
summaryTable$Gross_R <- ltaTable$Gross_R - ff*ltaTable$Q
#summaryTable$ETGW <- ltaTable$ETGW
summaryTable$ETGW <- summaryTable$net_R-summaryTable$Gross_R
summaryTable$ETtot <- ltaTable$OS_T+ltaTable$US_T+ltaTable$Soil_E+ltaTable$OS_i+ltaTable$US_i
```

# now I need to plot a curve for each groundwater depth, for each soil, climate veg combination.

```
climateList <- summaryTable$climate
climateList <- gsub(".clm","",climateList)
depthList <- gsub("[^0-9]", "", climateList)
depthListUnique <- unique(depthList)
climateList <- gsub("[0-9]", "", climateList)
climateListUnique <- unique(climateList)
soilList <- gsub(".tab","",summaryTable$Soil)
soilListUnique <- unique(gsub(".tab","",summaryTable$Soil))
vegList <- gsub(".veg","",summaryTable$Veg)
vegListUnique <- unique(gsub(".veg","",summaryTable$Veg))
```

```
combList <- expand.grid(climateListUnique,soilListUnique,vegListUnique)
```

```

combList$Var4 <- do.call(paste, c(combList[c("Var1", "Var2", "Var3")], sep = "_"))
summaryTable$clim <- gsub("[0-9]", "", summaryTable$climate)
summaryTable$index <- do.call(paste, c(summaryTable[c("clim", "Soil", "Veg")], sep = "_"))
summaryTable$depth <- gsub("[^0-9]", "", summaryTable$climate)
summaryTable$index <- gsub(".veg", "", summaryTable$index)
summaryTable$index <- gsub(".tab", "", summaryTable$index)
summaryTable$index <- gsub(".clm", "", summaryTable$index)

xrech100 <- array(0,dim=length(depthListUnique))
xrech50 <- array(0,dim=length(depthListUnique))
yAxis <- array(0,dim=length(depthListUnique))
test <- array(0,dim=length(depthListUnique))

# Define CSIRO standard colours

Midday <- rgb(0, 169, 206, max = 255)
Midnight <- rgb(0, 49, 60, max = 255)
Lavender <- rgb(159, 174, 229, max = 255)
Blue_berry <- rgb(30, 34, 170, max = 255)
Sky_blue <- rgb(65, 182, 230, max = 255)
Ocean_blue <- rgb(0, 75, 135, max = 255)
Light_tea <- rgb(45, 204, 211, max = 255)
Dark_tea <- rgb(0, 115, 119, max = 255)
Light_mint <- rgb(55, 204, 152, max = 255)
Dark_mint <- rgb(100, 122, 83, max = 255)
Light_forest <- rgb(120, 190, 32, max = 255)
Dark_forest <- rgb(68, 105, 61, max = 255)
Plum <- rgb(109, 32, 119, max = 255)
Fuschia <- rgb(223, 25, 149, max = 255)
Vermillion <- rgb(228, 0, 43, max = 255)
Orange_ <- rgb(232, 119, 34, max = 255)
Gold <- rgb(255, 184, 28, max = 255)

#pal <- myColours

#####% % % % % % % % % % @ @ @ @ @ @ @ @ ***** CHANGE VEG HERE
#####*****& & & & & % @ @ @ @ @ @ @ @ @ @

vegTypeRun <- v # crops, Native_Veg, pasture, softwoods
lineNumsVeg <- which(gsub(".",veg","",summaryTable$Veg) == vegTypeRun)

#yAxis <- array(c(0.01, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18,
20, 22, 24),dim=c(1,28)) #28
#netRdf <- data.frame(yAxis, row.names="DTW")

#fileList <-
c("MtGamb.clm","Beachport.clm","BorderTown.clm","CapeNorth.clm","Dartmoor.clm","Edenhope.clm",
#"Goroke.clm","Kingston.clm","Lucindale.clm","MtBurr.clm","Naracoorte.clm","Penola.clm")

#fileList <- c("Dartmoor.clm",)

```

```

# use these if you want to plot out just one
#combSingle <- "MtGamb_soil2_softwoods"
#combSingle <- "MtGamb_soil5_Native_Veg"
#combSingle <- "BorderTown_soil5_crops"
#combSingle <- "Lucindale_soil5_pasture"
#combSingle <- "Lucindale_soil2_Native_Veg"

for (x in combList$Var4) { # use this to plot all figures
#for (x in combSingle) { # use this to plot out only one combination
  #count <- which(combList$Var4 == x)
  graphTitle <- x

  pointer <- which(summaryTable$index == x)

  if (length(intersect(pointer, lineNumsVeg)) > 0) {

    for (y in length(depthListUnique)) {

      #xrech100 <- array(-1*summaryTable$rech100[which(summaryTable$index == x)],dim =
length(depthListUnique))
      #xrech50 <- array(-1*summaryTable$rech50[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xnet_R <- array(-1*summaryTable$net_R[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xOS_T <- array(-1*summaryTable$OS_T[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xUS_T <- array(-1*summaryTable$US_T[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xLAI_O <- array(-1*summaryTable$LAI_O[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xLAI_U <- array(-1*summaryTable$LAI_U[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xSoil_E <- array(-1*summaryTable$Soil_E[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xQ <- array(-1*summaryTable$Q[which(summaryTable$index == x)],dim = length(depthListUnique))
      xOS_i <- array(-1*summaryTable$OS_i[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xUS_i <- array(-1*summaryTable$US_i[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xGross_R <- array(-1*summaryTable$Gross_R[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xETGW <- array(-1*summaryTable$ETGW[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xETtot <- array(-1*summaryTable$ETtot[which(summaryTable$index == x)],dim =
length(depthListUnique))

      xLAI_O <- xLAI_O/36.5
      xLAI_U <- xLAI_U/36.5
      xnet_T <- xOS_T + xUS_T
      xnet_LAI <- xLAI_O + xLAI_U
      xnet_i <- xOS_i + xUS_i
    }
  }
}

```

```

yAxis <- array(as.numeric(summaryTable$depth[which(summaryTable$index == x)]/(100),dim =
length(depthListUnique))

# as depth expressed as cm in file

#divide by years, make negative

}

#Vermillion, Orange_, Gold, Light_forest, Dark_tea, Sky_blue, Ocean_blue, Lavender, Plum, Midnight

# myColours <- c(Vermillion, Orange_, Gold, Light_forest, Dark_tea, Sky_blue, Ocean_blue, Lavender,
Plum, Fuschia, #Dark_mint,
#           Midnight)

myColours <- c(Vermillion, Orange_, Gold, Light_forest, Dark_tea, Lavender, Midnight)

# legText <- c("OS_T", "US_T", "OS_i", "US_i", "OS_LAI(x10)", "US_LAI(x10)", "Soil_E", "Q", "Gross_R",
"ETGW", #"ETtot",
#           "net_R")
legText <- c("OS_T", "OS_i", "Soil_E", "Q", "Gross_R", "ETGW", "net_R")

# plot(xOS_T, yAxis, type = "l", main = graphTitle, xlab = "Flux (mm/y)", ylab = "DTW (m)", xlim=c(-1000,
300), ylim=c(-22, 0), col=Vermillion)
## lines(xUS_T, yAxis, type = "l", col=Orange_)
# lines(xOS_i, yAxis, type = "l", col=Gold)
## lines(xUS_i, yAxis, type = "l", col=Light_forest)
## lines(xLAI_O, yAxis, type = "l", col=Dark_tea)
## lines(xLAI_U, yAxis, type = "l", col=Sky_blue)
# lines(xSoil_E, yAxis, type = "l", col=Ocean_blue)
# lines(xQ, yAxis, type = "l", col=Lavender)
# lines(xGross_R, yAxis, type = "l", col=Plum)
# lines(xETGW, yAxis, type = "l", col=Fuschia)
## lines(xETtot, yAxis, type = "l", col=Dark_mint)
# lines(xnet_R, yAxis, type = "l", col=Midnight, lwd=2)

plot(xOS_T, yAxis, type = "l", main = graphTitle, xlab = "Flux (mm/y)", ylab = "DTWT (m)", xlim=c(-1000,
300), ylim=c(13, 0), col=Vermillion)
# lines(xUS_T, yAxis, type = "l", col=Orange_)
lines(xOS_i, yAxis, type = "l", col=Orange_)
# lines(xUS_i, yAxis, type = "l", col=Light_forest)
# lines(xLAI_O, yAxis, type = "l", col=Dark_tea)
# lines(xLAI_U, yAxis, type = "l", col=Sky_blue)
lines(xSoil_E, yAxis, type = "l", col=Gold)
lines(xQ, yAxis, type = "l", col=Light_forest)
lines(xGross_R, yAxis, type = "l", col=Dark_tea)
lines(xETGW, yAxis, type = "l", col=Lavender)
# lines(xETtot, yAxis, type = "l", col=Dark_mint)
lines(xnet_R, yAxis, type = "l", col=Midnight, lwd=2)

```

```

# plot out here

# dat <- matrix(c(xnet_R, xOS_T, xUS_T, xLAI_O, xLAI_U, xSoil_E, xQ, xOS_i, xUS_i, xGross_R,
yAxis),ncol=11) # make data
# matplot(dat, type = c("b"),pch=1,col = 1:10) #plot
  legend("bottomleft", legend = legText, col=myColours, pch=1, bty='n') # optional legend

}

}

}

}

dev.off()

#####write out as a file for MODFLOW#####

#Need to run the section immediately above first...

fileTagList <- c("MtGamb","Beach","BT","CapeN","Dart","Eden",
  "Goroke","Kingston","Lucindale","MtBurr","Naracoorte","Penola")

i <- "Dart" # make this loop later on.

fpath <- "//wron/working/work/doble/Goyder/WAVES/WAVESoutputs/"

summaryTable <- read.table(file=paste(fpath,"summary",i,".txt",sep=""), header = TRUE)

ltaTable <- read.table(file=paste(fpath,"100yr_ave",i,".txt",sep=""), header = TRUE)

climateList <- summaryTable$climate
climateList <- gsub(".clm","",climateList)
depthList <- gsub("^[0-9]","",climateList)
depthListUnique <- unique(depthList)
climateList <- gsub("[0-9]","",climateList)
climateListUnique <- unique(climateList)
soilList <- gsub(".tab","",summaryTable$Soil)
soilListUnique <- unique(gsub(".tab","",summaryTable$Soil))
vegList <- gsub(".veg","",summaryTable$Veg)
vegListUnique <- unique(gsub(".veg","",summaryTable$Veg))

combList <- expand.grid(climateListUnique,soilListUnique,vegListUnique)

combList$Var4 <- do.call(paste, c(combList[c("Var1", "Var2", "Var3")], sep = "_"))
#summaryTable$index <- c(climateList, soilList, vegList, sep = "")
summaryTable$clim <- gsub("[0-9]","",summaryTable$climate)

```



```

summaryTable$index <- do.call(paste, c(summaryTable[c("clim", "Soil", "Veg")], sep = "_"))
summaryTable$depth <- gsub("[^0-9]", "", summaryTable$climate)
summaryTable$index <- gsub(".veg", "", summaryTable$index)
summaryTable$index <- gsub(".tab", "", summaryTable$index)
summaryTable$index <- gsub(".clm", "", summaryTable$index)
#summaryTable$index <- gsub("[0-9]", "", summaryTable$index)

xrech100 <- array(0,dim=length(depthListUnique))
xrech50 <- array(0,dim=length(depthListUnique))
#yAxis <- array(0,dim=length(depthListUnique))
test <- array(0,dim=length(depthListUnique))
yAxis <- array(as.numeric(summaryTable$depth[which(summaryTable$index == x)])/(-100),dim =
c(1,length(depthListUnique)))

#yAxis <- array(c(0.01, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18,
20),dim=c(1,26)) #26
#depthListWrite <- array(depthList, dim=c(1,28))
netRdf <- data.frame(yAxis, row.names="DTW")

for (x in combList$Var4) {
  count <- which(combList$Var4 == x)
  # graphTitle <- x
  #print(x)
  pointer <- which(summaryTable$index == x)

  # if (length(intersect(pointer, lineNumsVeg)) > 0) {

    for (y in length(depthListUnique)) {

      #xrech100 <- array(-1*summaryTable$rech100[which(summaryTable$index == x)],dim =
length(depthListUnique))
      #xrech50 <- array(-1*summaryTable$rech50[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xnet_R <- array(-1*summaryTable$net_R[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xOS_T <- array(-1*summaryTable$OS_T[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xUS_T <- array(-1*summaryTable$US_T[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xLAI_O <- array(-1*summaryTable$LAI_O[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xLAI_U <- array(-1*summaryTable$LAI_U[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xSoil_E <- array(-1*summaryTable$Soil_E[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xQ <- array(-1*summaryTable$Q[which(summaryTable$index == x)],dim = length(depthListUnique))
      xOS_i <- array(-1*summaryTable$OS_i[which(summaryTable$index == x)],dim =
length(depthListUnique))
      xUS_i <- array(-1*summaryTable$US_i[which(summaryTable$index == x)],dim =
length(depthListUnique))

```

```

xGross_R <- array(-1*summaryTable$Gross_R[which(summaryTable$index == x)],dim =
length(depthListUnique))

xLAI_O <- xLAI_O/36.5
xLAI_U <- xLAI_U/36.5
xnet_T <- xOS_T + xUS_T
xnet_LAI <- xLAI_O + xLAI_U
xnet_i <- xOS_i + xUS_i

yAxis <- array(as.numeric(summaryTable$depth[which(summaryTable$index == x)])/(-100),dim =
length(depthListUnique))

# as depth expressed as cm in file

#divide by years, make negative

}

# compile into matrix and write out as text file
newRow <- array(xnet_R, dim=c(1,26))
newRow <- data.frame(newRow, row.names=x)
netRdf <- rbind(netRdf, newRow)
# }

}

write.table(netRdf, file=paste(fpath,"MODFLOW_",i,".txt",sep=""), row.names=TRUE, col.names=FALSE,
sep=" ")

##### Bit to plot out the CMRSET data from Russell

# read in output files
fpath <- "//wron/working/work/doble/Goyder/WAVES/CMRSET/"

rechTable <- read.table(file=paste(fpath,"DTW_Soil_Veg.txt",sep=""), header = TRUE, nrows = 371364,
comment.char = "")
#rechTable <- scan(file=paste(fpath,"Depth_Soil_Veg.csv",sep=""), sep=",")

vegType <- rechTable$Veg
soilType <- rechTable$PC_class
dtw <- rechTable$DTW
rechTable$B_C_R <- rechTable$B_C_R-45 # with bias bias correction!
netR <- rechTable$B_C_R #Bias corrected R (I have added 45mm/a on to the CMRSET data)

##### CHANGE THIS FOR EACH OF THE DIFFERENT VEGETATION TYPES
vegTypeRun <- "Pastures" # Crops, Hardwood, Irrigated, NativeVeg, Pastures, Softwood

lineNumsVeg <- which(rechTable$Veg == vegTypeRun)

par(mfrow = c(3,3))

```

```

soilList <- array(rechTable$PC_class)
soilList <- unique(soilList)

subsetTable1 <- subset(rechTable , Veg == vegTypeRun & PC_class == "1")
xSoil1 <- subsetTable1$B_C_R
ySoil1 <- subsetTable1$DTW

subsetTable2 <- subset(rechTable , Veg == vegTypeRun & PC_class == "2")
xSoil2 <- subsetTable2$B_C_R
ySoil2 <- subsetTable2$DTW

subsetTable3 <- subset(rechTable , Veg == vegTypeRun & PC_class == "3")
xSoil3 <- subsetTable3$B_C_R
ySoil3 <- subsetTable3$DTW

subsetTable4 <- subset(rechTable , Veg == vegTypeRun & PC_class == "4")
xSoil4 <- subsetTable4$B_C_R
ySoil4 <- subsetTable4$DTW

subsetTable5 <- subset(rechTable , Veg == vegTypeRun & PC_class == "5")
xSoil5 <- subsetTable5$B_C_R
ySoil5 <- subsetTable5$DTW

subsetTable6 <- subset(rechTable , Veg == vegTypeRun & PC_class == "6")
xSoil6 <- subsetTable6$B_C_R
ySoil6 <- subsetTable6$DTW

subsetTable7 <- subset(rechTable , Veg == vegTypeRun & PC_class == "7")
xSoil7 <- subsetTable7$B_C_R
ySoil7 <- subsetTable7$DTW

#legText <- c("OS_T", "US_T", "OS_i", "US_i", "OS_LAI(x10)", "US_LAI(x10)", "Soil_E", "Q", "Gross_R",
"net_R")
#plot(xSoil1, ySoil1, type = "p", main = c(vegTypeRun,"Soil_1", sep = " "), xlab = "Net Recharge (mm/y)",
ylab = "DTW (m)", xlim=c(-400, 200), ylim=c(0, 22))
#plot(xSoil2, ySoil2, type = "p", main = c(vegTypeRun,"Soil_2", sep = " "), xlab = "Net Recharge (mm/y)",
ylab = "DTW (m)", xlim=c(-400, 200), ylim=c(0, 22))
#plot(xSoil3, ySoil3, type = "p", main = c(vegTypeRun,"Soil_3", sep = " "), xlab = "Net Recharge (mm/y)",
ylab = "DTW (m)", xlim=c(-400, 200), ylim=c(0, 22))
#plot(xSoil4, ySoil4, type = "p", main = c(vegTypeRun,"Soil_4", sep = " "), xlab = "Net Recharge (mm/y)",
ylab = "DTW (m)", xlim=c(-400, 200), ylim=c(0, 22))
#plot(xSoil5, ySoil5, type = "p", main = c(vegTypeRun,"Soil_5", sep = " "), xlab = "Net Recharge (mm/y)",
ylab = "DTW (m)", xlim=c(-400, 200), ylim=c(0, 22))
#plot(xSoil6, ySoil6, type = "p", main = c(vegTypeRun,"Soil_6", sep = " "), xlab = "Net Recharge (mm/y)",
ylab = "DTW (m)", xlim=c(-400, 200), ylim=c(0, 22))
#plot(xSoil7, ySoil7, type = "p", main = c(vegTypeRun,"Soil_7", sep = " "), xlab = "Net Recharge (mm/y)",
ylab = "DTW (m)", xlim=c(-400, 200), ylim=c(0, 22))

# for each soil type, need a table of recharge then soil depth

soilTable1 <- setNames(data.frame(v1=xSoil1, v2=ySoil1), c("netR","DTW"))
soilTable2 <- setNames(data.frame(v1=xSoil2, v2=ySoil2), c("netR","DTW"))

```

```

soilTable3 <- setNames(data.frame(v1=xSoil3, v2=ySoil3), c("netR","DTW"))
soilTable4 <- setNames(data.frame(v1=xSoil4, v2=ySoil4), c("netR","DTW"))
soilTable5 <- setNames(data.frame(v1=xSoil5, v2=ySoil5), c("netR","DTW"))
soilTable6 <- setNames(data.frame(v1=xSoil6, v2=ySoil6), c("netR","DTW"))
soilTable7 <- setNames(data.frame(v1=xSoil7, v2=ySoil7), c("netR","DTW"))

par(mfrow = c(3,3))

##TRY ggplot2
#p <- ggplot(data = soilTable1, aes(factor(DTW), netR))
#
#p + geom_boxplot() + coord_flip() + coord_cartesian(xlim=c(0, 25))
# scale_x_continuous(breaks=seq(0, 20, 2)) # Ticks from 0-10, every .25
# + scale_x_discrete(breaks = c(0,1.5,3.5,5.5,7.5,9.5,11.5,13.5,15.5,17.5,19.5,21.5,23.5,25.5))

# for each of these plot n as a bar chart behind the box plots.
*****

##### Soil1
boxplot(netR~DTW,data=soilTable1, main= c(vegTypeRun," Soil 1",sep=""),
  xlab="DTW (m)",
  ylab="Net Recharge (mm/yr)", xlim=c(0,25), ylim=c(-350,350),
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
  pars = list(boxwex = 0.6,
  staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
  cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
depthlist <- unique(soilTable1$DTW) #x axis
depthNum <- array(1:length(depthlist))
netRMean <- array(0, dim=length(depthlist))

for (x in depthlist){
  netRMean[depthNum[which(depthlist==x)]] <- mean(soilTable1$netR[which(soilTable1$DTW==x)])
}
lines(depthlist, netRMean, type = "l", col=Vermillion)
#####

##### Soil2
boxplot(netR~DTW,data=soilTable2, main= c(vegTypeRun," Soil 2",sep=""),
  xlab="DTW (m)",
  ylab="Net Recharge (mm/yr)", xlim=c(0,25), ylim=c(-350,350),
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
  pars = list(boxwex = 0.6,
  staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
  cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
depthlist <- unique(soilTable2$DTW) #x axis
depthNum <- array(1:length(depthlist))
netRMean <- array(0, dim=length(depthlist))

for (x in depthlist){
  netRMean[depthNum[which(depthlist==x)]] <- mean(soilTable2$netR[which(soilTable2$DTW==x)])
}
lines(depthlist, netRMean, type = "l", col=Vermillion)

```

```
#####

##### Soil3
boxplot(netR~DTW,data=soilTable3, main= c(vegTypeRun," Soil 3",sep=""),
  xlab="DTW (m)",
  ylab="Net Recharge (mm/yr)", xlim=c(0,25), ylim=c(-350,350),
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
  pars = list(boxwex = 0.6,
  staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
  cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
depthlist <- unique(soilTable3$DTW) #x axis
depthNum <- array(1:length(depthlist))
netRMean <- array(0, dim=length(depthlist))

for (x in depthlist){
  netRMean[depthNum[which(depthlist==x)]] <- mean(soilTable3$netR[which(soilTable3$DTW==x)])
}
lines(depthlist, netRMean, type = "l", col=Vermillion)
#####

##### Soil4
boxplot(netR~DTW,data=soilTable4, main= c(vegTypeRun," Soil 4",sep=""),
  xlab="DTW (m)",
  ylab="Net Recharge (mm/yr)", xlim=c(0,25), ylim=c(-350,350),
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
  pars = list(boxwex = 0.6,
  staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
  cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
depthlist <- unique(soilTable4$DTW) #x axis
depthNum <- array(1:length(depthlist))
netRMean <- array(0, dim=length(depthlist))

for (x in depthlist){
  netRMean[depthNum[which(depthlist==x)]] <- mean(soilTable4$netR[which(soilTable4$DTW==x)])
}
lines(depthlist, netRMean, type = "l", col=Vermillion)
#####

##### Soil5
boxplot(netR~DTW,data=soilTable5, main= c(vegTypeRun," Soil 5",sep=""),
  xlab="DTW (m)",
  ylab="Net Recharge (mm/yr)", xlim=c(0,25), ylim=c(-350,350),
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
  pars = list(boxwex = 0.6,
  staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
  cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
depthlist <- unique(soilTable5$DTW) #x axis
depthNum <- array(1:length(depthlist))
netRMean <- array(0, dim=length(depthlist))

for (x in depthlist){
  netRMean[depthNum[which(depthlist==x)]] <- mean(soilTable5$netR[which(soilTable5$DTW==x)])
}
lines(depthlist, netRMean, type = "l", col=Vermillion)
```

```
#####

##### Soil6
boxplot(netR~DTW,data=soilTable6, main= c(vegTypeRun," Soil 6",sep=""),
  xlab="DTW (m)",
  ylab="Net Recharge (mm/yr)", xlim=c(0,25), ylim=c(-350,350),
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
  pars = list(boxwex = 0.6,
  staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
  cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
depthlist <- unique(soilTable6$DTW) #x axis
depthNum <- array(1:length(depthlist))
netRMean <- array(0, dim=length(depthlist))

for (x in depthlist){
  netRMean[depthNum[which(depthlist==x)]] <- mean(soilTable6$netR[which(soilTable6$DTW==x)])
}
lines(depthlist, netRMean, type = "l", col=Vermillion)
#####

##### Soil7
boxplot(netR~DTW,data=soilTable7, main= c(vegTypeRun," Soil 7",sep=""),
  xlab="DTW (m)",
  ylab="Net Recharge (mm/yr)", xlim=c(0,32),
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
  pars = list(boxwex = 0.6,
  staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
  cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
depthlist <- unique(soilTable7$DTW) #x axis
depthNum <- array(1:length(depthlist))
netRMean <- array(0, dim=length(depthlist))

for (x in depthlist){
  netRMean[depthNum[which(depthlist==x)]] <- mean(soilTable7$netR[which(soilTable7$DTW==x)])
}
lines(depthlist, netRMean, type = "l", col=Vermillion)
#####
```

### C.3 R code for

```
# Script to calibrate the WAVES outputs with CMRSET net recharge data
# Goyder SE work
```

```
library(sp)
library(zoo)
library(xts)
library(spacetime)
library(gstat)
library(raster)
library(rgdal)
library(ncdf)
library(qdapTools)
```



```
library(ggplot2)
```

```
#fpath <- "//FILE-WRON/working/work/rrf/Goyder_SE/GIS/lookup_table_raster/"
fpath <- "x:/work/rrf/Goyder_SE/GIS/lookup_table_raster/"
#fpathMF <- "x:/work/rrf/Goyder_SE/GIS/lookup_table_raster/"
#fpathMF <- "Z:/Goyder/WAVES/WAVESNov14/"
#fpathMF <- "Z:/Goyder/WAVES/RussellCalib/" #@@@@@@@@@@@@@@@@@@@@
#fpathMF <- "Z:/Goyder/WAVES/WAVESFeb15/"
fpathMF <- "X:/work/RRF/Goyder_SE/WAVES/Feb15_2/"
fpathDTWT <- "Z:/Goyder/Flinders/"
```

```
# Open the lookup table
# Open the raster key
# Open the depth to groundwater raster
# For each raster cell, take the key identifier and groundwater depth, and return a value for net recharge
# If the key does not exist, return -999
# Write the out the resulting recharge raster
# Print the resulting raster as a graphic
```

```
# Read in the CMRSET recharge raster
# Perform a statistical analysis of performance (!!)
```

- # Look at which of the climate/soil/landuse overestimate, underestimate or are ok.
- # Do this by plotting the pixel 'error' (how to define) against depth for each climate/soil/landuse
- # Scatter plot of all data
- # Scatter plot for each soil and veg combination (42)
- # Residuals vs depth for each soil veg combo
- # Relative residuals vs depth for each soil veg combo
- # Is there any way to translate this to how much we should change the WAVES data by?

```
# Open the lookup table (WAVES data) * any way to do this line by line? think about it.
#lookupTable <- read.table(paste(fpathMF,"MODFLOW_Code.txt",sep=""), header= TRUE) # mm/year
annual average
#lookupTable <- read.table(paste(fpathMF,"MODFLOW_Code8veg.txt",sep=""), header= TRUE) # mm/year
annual average
#@#@#@#@lookupTable <- read.table(paste(fpathMF,"MODFLOW_ETCode8veg.txt",sep=""), header=
TRUE) # mm/year annual average
#lookupTable <- read.table(paste(fpathMF,"MODFLOW_CodeFeb.txt",sep=""), header= TRUE) # mm/year
annual average
lookupTable <- read.table(paste(fpathMF,"MODFLOW_Code2.txt",sep=""), header= TRUE) # mm/year
annual average
```

```
# Open the raster key
#rasterKey <- raster(paste(fpath,"raster_key",sep=""))
rasterKey <- raster(paste(fpath,"raster_key3",sep=""))
```

```
# Open the depth to groundwater raster
#dtwt <- raster(paste(fpath,"dtwt",sep="")) #metres
#dtwt <- raster(paste(fpathDTWT,"RSWL_Ave_2008",sep="")) #metres
dtwt <- raster(paste(fpathDTWT,"dtwt250",sep="")) #metres # this is the 2008 DTWT
vegMap <- raster(paste(fpath,"veg2",sep="")) #metres
```

```

soilsMap <- raster(paste(fpath,"soils2",sep="")) #metres

#MODISet <- raster(paste(fpathDTWT,"MODIS_ET\2008\aet_mean_mmy_2008_mgaz54",sep="")) #metres

dtwt <- resample(dtwt, vegMap, method='bilinear')

# add nominal depth to dtwt to account for inaccuracies.
#dtwt[] <- dtwt[] + 2.0
#dtwt[] <- dtwt[]

# For each raster cell, take the key identifier and groundwater depth, and return a value for net recharge
rech <- rasterKey
rech[] <- 0

ncols <- ncol(rasterKey)
nrows <- nrow(rasterKey)

# testing with one value
# key <- 111
# depth <- 3.1

#Try one raster for each depth.
lookupDepth <- names(lookupTable)
#get rid of the "DTW"
lookupDepth <- lookupDepth[-1]

code <- lookupTable$DTW

# trying to get this to work using lookup.

rech <- as.vector(rasterKey)

rech0 <- rasterKey
df <- data.frame(code,lookupTable[,2])
rech0 <- lookup(rech, df)
#rech0 <- setValues(rasterKey,rech0)

rech0_01 <- rasterKey
df <- data.frame(code,lookupTable[,3])
rech0_01 <- lookup(rech, df)
#rech0_01 <- setValues(rasterKey,rech0_01)

rech0_05 <- rasterKey
df <- data.frame(code,lookupTable[,4])
rech0_05 <- lookup(rech, df)
#rech0_05 <- setValues(rasterKey,rech0_05)

rech0_1 <- rasterKey
df <- data.frame(code,lookupTable[,5])

```

```

rech0_1 <- lookup(rech, df)
#rech0_1 <- setValues(rasterKey, rech0_1)

rech0_2 <- rasterKey
df <- data.frame(code, lookupTable[,6])
rech0_2 <- lookup(rech, df)
#rech0_2 <- setValues(rasterKey, rech0_2)

rech0_4 <- rasterKey
df <- data.frame(code, lookupTable[,7])
rech0_4 <- lookup(rech, df)
#rech0_4 <- setValues(rasterKey, rech0_4)

rech0_6 <- rasterKey
df <- data.frame(code, lookupTable[,8])
rech0_6 <- lookup(rech, df)
#rech0_6 <- setValues(rasterKey, rech0_6)

rech0_8 <- rasterKey
df <- data.frame(code, lookupTable[,9])
rech0_8 <- lookup(rech, df)
#rech0_8 <- setValues(rasterKey, rech0_8)

rech1 <- rasterKey
df <- data.frame(code, lookupTable[,10])
rech1 <- lookup(rech, df)
#rech1 <- setValues(rasterKey, rech1)

rech1_5 <- rasterKey
df <- data.frame(code, lookupTable[,11])
rech1_5 <- lookup(rech, df)
#rech1.5 <- setValues(rasterKey, rech1.5)

rech2 <- rasterKey
df <- data.frame(code, lookupTable[,12])
rech2 <- lookup(rech, df)
#rech2 <- setValues(rasterKey, rech2)

rech2_5 <- rasterKey
df <- data.frame(code, lookupTable[,13])
rech2_5 <- lookup(rech, df)
#rech2.5 <- setValues(rasterKey, rech2.5)

rech3 <- rasterKey
df <- data.frame(code, lookupTable[,14])
rech3 <- lookup(rech, df)
#rech3 <- setValues(rasterKey, rech3)

rech3_5 <- rasterKey
df <- data.frame(code, lookupTable[,15])
rech3_5 <- lookup(rech, df)
#rech3.5 <- setValues(rasterKey, rech3.5)

rech4 <- rasterKey

```

```

df <- data.frame(code,lookupTable[,16])
rech4 <- lookup(rech, df)
#rech4 <- setValues(rasterKey,rech4)

rech4_5 <- rasterKey
df <- data.frame(code,lookupTable[,17])
rech4_5 <- lookup(rech, df)
#rech4.5 <- setValues(rasterKey,rech4.5)

rech5 <- rasterKey
df <- data.frame(code,lookupTable[,18])
rech5 <- lookup(rech, df)
#rech5 <- setValues(rasterKey,rech5)

rech6 <- rasterKey
df <- data.frame(code,lookupTable[,19])
rech6 <- lookup(rech, df)
#rech6 <- setValues(rasterKey,rech6)

rech7 <- rasterKey
df <- data.frame(code,lookupTable[,20])
rech7 <- lookup(rech, df)
#rech7 <- setValues(rasterKey,rech7)

rech8 <- rasterKey
df <- data.frame(code,lookupTable[,21])
rech8 <- lookup(rech, df)
#rech8 <- setValues(rasterKey,rech8)

rech9 <- rasterKey
df <- data.frame(code,lookupTable[,22])
rech9 <- lookup(rech, df)
#rech9 <- setValues(rasterKey,rech9)

rech10 <- rasterKey
df <- data.frame(code,lookupTable[,23])
rech10 <- lookup(rech, df)
#rech10 <- setValues(rasterKey,rech10)

rech12 <- rasterKey
df <- data.frame(code,lookupTable[,24])
rech12 <- lookup(rech, df)
#rech12 <- setValues(rasterKey,rech12)

rech14 <- rasterKey
df <- data.frame(code,lookupTable[,25])
rech14 <- lookup(rech, df)
#rech14 <- setValues(rasterKey,rech14)

rech16 <- rasterKey
df <- data.frame(code,lookupTable[,26])
rech16 <- lookup(rech, df)
#rech16 <- setValues(rasterKey,rech16)

```

```

rech18 <- rasterKey
df <- data.frame(code,lookupTable[,27])
rech18 <- lookup(rech, df)
#rech18 <- setValues(rasterKey,rech18)

rech20 <- rasterKey
df <- data.frame(code,lookupTable[,28])
rech20 <- lookup(rech, df)
#rech20 <- setValues(rasterKey,rech20)

# now get the dtwt raster, turn it into a vector and do the lookup function on it.

depth <- as.vector(dtwt)
rechNet <- as.vector(dtwt) # this has to be identical to the lookup key raster
rechUpper <- as.vector(dtwt) # this has to be identical to the lookup key raster
rechLower <- as.vector(dtwt) # this has to be identical to the lookup key raster
depthUpper <- as.vector(dtwt) # this has to be identical to the lookup key raster
depthLower <- as.vector(dtwt) # this has to be identical to the lookup key raster

#df <- data.frame(lookupDepth,rech_0)

rechUpper <- ifelse (is.na(depth), NA, ifelse(depth<0,rech0, ifelse(depth>20, rech20, rechUpper)))
rechLower <- ifelse (is.na(depth), NA, ifelse(depth<0,rech0, ifelse(depth>20, rech20, rechLower)))
depthUpper <- ifelse (is.na(depth), NA, ifelse(depth<0,0, ifelse(depth>20, 20, depthUpper)))
depthLower <- ifelse (is.na(depth), NA, ifelse(depth<0,0, ifelse(depth>20, 20, depthLower)))

## If depthupper - depthLower = 0, then make it equal to depth and rech upper.

#c(rech,20,sep="")

lookupDepth <- c(0,0.01,0.05,0.1,0.2,0.4,0.6,0.8,1,1.5,2,2.5,3,3.5,4,4.5,5,6,7,8,9,10,12,14,16,18,20)

#perhaps replace depth values in rechDepthUpper with parameters to call?

r20plus <- which((depth>=20))
r20 <- which((depth<20 & depth>=18))
r18 <- which((depth<18 & depth>=16))
r16 <- which((depth<16 & depth>=14))
r14 <- which((depth<14 & depth>=12))
r12 <- which((depth<12 & depth>=10))
r10 <- which((depth<10 & depth>=9))
r9 <- which((depth<9 & depth>=8))
r8 <- which((depth<8 & depth>=7))
r7 <- which((depth<7 & depth>=6))
r6 <- which((depth<6 & depth>=5))
r5 <- which((depth<5 & depth>=4.5))
r4_5 <- which((depth<4.5 & depth>=4))
r4 <- which((depth<4 & depth>=3.5))
r3_5 <- which((depth<3.5 & depth>=3))
r3 <- which((depth<3 & depth>=2.5))
r2_5 <- which((depth<2.5 & depth>=2))
r2 <- which((depth<2 & depth>=1.5))
r1_5 <- which((depth<1.5 & depth>=1))
r1 <- which((depth<1 & depth>=0.8))

```

```

r0_8 <- which((depth<0.8 & depth>=0.6))
r0_6 <- which((depth<0.6 & depth>=0.4))
r0_4 <- which((depth<0.4 & depth>=0.2))
r0_2 <- which((depth<0.2 & depth>=0.1))
r0_1 <- which((depth<0.1 & depth>=0.05))
r0_05 <- which((depth<0.05 & depth>=0.01))
r0_01 <- which((depth<0.01 & depth>=0))
r0 <- which(depth<0)

```

```

rechUpper[r20plus] <- rech20[r20plus]
rechUpper[r20] <- rech20[r20]
rechUpper[r18] <- rech18[r18]
rechUpper[r16] <- rech16[r16]
rechUpper[r14] <- rech14[r14]
rechUpper[r12] <- rech12[r12]
rechUpper[r10] <- rech10[r10]
rechUpper[r9] <- rech9[r9]
rechUpper[r8] <- rech8[r8]
rechUpper[r7] <- rech7[r7]
rechUpper[r6] <- rech6[r6]
rechUpper[r5] <- rech5[r5]
rechUpper[r4_5] <- rech4_5[r4_5]
rechUpper[r4] <- rech4[r4]
rechUpper[r3_5] <- rech3_5[r3_5]
rechUpper[r3] <- rech3[r3]
rechUpper[r2_5] <- rech2_5[r2_5]
rechUpper[r2] <- rech2[r2]
rechUpper[r1_5] <- rech1_5[r1_5]
rechUpper[r1] <- rech1[r1]
rechUpper[r0_8] <- rech0_8[r0_8]
rechUpper[r0_6] <- rech0_6[r0_6]
rechUpper[r0_4] <- rech0_4[r0_4]
rechUpper[r0_2] <- rech0_2[r0_2]
rechUpper[r0_1] <- rech0_1[r0_1]
rechUpper[r0_05] <- rech0_05[r0_05]
rechUpper[r0_01] <- rech0_01[r0_01]
rechUpper[r0] <- rech0[r0]

```

```

#rechUpper <- setValues(rasterKey,rechUpper)

```

```

rechLower[r20plus] <- rech20[r20plus]
rechLower[r20] <- rech18[r20]
rechLower[r18] <- rech16[r18]
rechLower[r16] <- rech14[r16]
rechLower[r14] <- rech12[r14]
rechLower[r12] <- rech10[r12]
rechLower[r10] <- rech9[r10]
rechLower[r9] <- rech8[r9]
rechLower[r8] <- rech7[r8]
rechLower[r7] <- rech6[r7]
rechLower[r6] <- rech5[r6]
rechLower[r5] <- rech4_5[r5]
rechLower[r4_5] <- rech4[r4_5]

```



```

rechLower[r4] <- rech3_5[r4]
rechLower[r3_5] <- rech3[r3_5]
rechLower[r3] <- rech2_5[r3]
rechLower[r2_5] <- rech2[r2_5]
rechLower[r2] <- rech1_5[r2]
rechLower[r1_5] <- rech1[r1_5]
rechLower[r1] <- rech0_8[r1]
rechLower[r0_8] <- rech0_6[r0_8]
rechLower[r0_6] <- rech0_4[r0_6]
rechLower[r0_4] <- rech0_2[r0_4]
rechLower[r0_2] <- rech0_1[r0_2]
rechLower[r0_1] <- rech0_05[r0_1]
rechLower[r0_05] <- rech0_01[r0_05]
rechLower[r0_01] <- rech0[r0_01]
rechLower[r0] <- rech0[r0]

```

```

#rechLower <- setValues(rasterKey,rechLower)

```

```

depthUpper[r20plus] <- 25
depthUpper[r20] <- 20
depthUpper[r18] <- 18
depthUpper[r16] <- 16
depthUpper[r14] <- 14
depthUpper[r12] <- 12
depthUpper[r10] <- 10
depthUpper[r9] <- 9
depthUpper[r8] <- 8
depthUpper[r7] <- 7
depthUpper[r6] <- 6
depthUpper[r5] <- 5
depthUpper[r4_5] <- 4.5
depthUpper[r4] <- 4
depthUpper[r3_5] <- 3.5
depthUpper[r3] <- 3
depthUpper[r2_5] <- 2.5
depthUpper[r2] <- 2.0
depthUpper[r1_5] <- 1.5
depthUpper[r1] <- 1.0
depthUpper[r0_8] <- 0.8
depthUpper[r0_6] <- 0.6
depthUpper[r0_4] <- 0.4
depthUpper[r0_2] <- 0.2
depthUpper[r0_1] <- 0.1
depthUpper[r0_05] <- 0.05
depthUpper[r0_01] <- 0.01
depthUpper[r0] <- 0

```

```

depthLower[r20plus] <- 20
depthLower[r20] <- 18
depthLower[r18] <- 16
depthLower[r16] <- 14
depthLower[r14] <- 12
depthLower[r12] <- 10
depthLower[r10] <- 9

```

```

depthLower[r9] <- 8
depthLower[r8] <- 7
depthLower[r7] <- 6
depthLower[r6] <- 5
depthLower[r5] <- 4.5
depthLower[r4_5] <- 4
depthLower[r4] <- 3.5
depthLower[r3_5] <- 3
depthLower[r3] <- 2.5
depthLower[r2_5] <- 2
depthLower[r2] <- 1.5
depthLower[r1_5] <- 1
depthLower[r1] <- 0.8
depthLower[r0_8] <- 0.6
depthLower[r0_6] <- 0.4
depthLower[r0_4] <- 0.2
depthLower[r0_2] <- 0.1
depthLower[r0_1] <- 0.05
depthLower[r0_05] <- 0.01
depthLower[r0_01] <- 0
depthLower[r0] <- 0

# do the calculation then change <0 and >20

rechNet <- (depth-depthLower)/(depthUpper-depthLower)*(rechUpper-rechLower)+rechLower

rechNet[which(depth[]<=0)] <- rech0[which(depth[]<=0)]
rechNet[which(depth[]>=20)] <- rech20[which(depth[]>=20)]

#depth <- setValues(rasterKey,depth)
rechNet <- setValues(rasterKey,rechNet)
rechUpper <- setValues(rasterKey,rechUpper)
rechLower <- setValues(rasterKey,rechLower)
depthUpper <- setValues(rasterKey,depthUpper)
depthLower <- setValues(rasterKey,depthLower)

plot(rechNet)

writeRaster(rechNet,file = paste(fpathMF,"WAVESrechFeb15_2.tif",sep=""),format="GTiff",
overwrite=TRUE)
#writeRaster(rechNet,file = paste(fpathMF,"WAVES_ET_RussellCalib2.tif",sep=""),format="GTiff",
overwrite=TRUE)
#####

#loweredWTrech <- rechNet
#plot(CMRSET, zlim = c(-600,600))
plot(CMRSET2, zlim = c(-600,600))

writeRaster(CMRSET,file = paste(fpathMF,"CMRSETrech.tif",sep=""),format="GTiff", overwrite=TRUE)
#origRech <- rechNet
#diff <- newRech - rechNet
#plot(diff)

```

```

# read in an alternative CMRSET recharge raster
fpathCMRSET2 <- "z:/Goyder/WAVES/CMRSET/"
CMRSET2 <- raster(paste(fpathCMRSET2,"CMRSETrech_2008.tif",sep=""))

# Read in the CMRSET recharge raster

#fpathCMRSET <- "//FILE-WRON/working/work/RRF/Goyder_SE/Paper/"
fpathCMRSET <- "x:/work/RRF/Goyder_SE/Paper/"

CMRSET <- raster(paste(fpathCMRSET,"rch10yrnobias",sep=""))
#CMB <- raster("//FILE-WRON/project/GOYDERSE/Data/CMB/r_rech_med_PIII2") # not it!
CMB <- raster("p:/GOYDERSE/Data/CMB/r_rech_med_PIII2.tif")

unit <- rechNet/rechNet
clipCMRSET <- CMRSET*unit
clipCMB <- resample(CMB,CMRSET)
clipCMB <- clipCMB*unit

rechWav <- cellStats(rechNet, stat='mean', na.rm=TRUE)
rechCMR <- cellStats(clipCMB, stat='mean', na.rm=TRUE)

# Look at which of the climate/soil/landuse overestimate, underestimate or are ok.

# Do this by plotting the pixel 'error' (how to define) against depth for each climate/soil/landuse

# Scatter plot of all data

xData <- as.vector(CMRSET)
yData <- as.vector(rechNet)

df <- data.frame(x=xData, y=yData)
#ggplot(df,aes(x=x, y=y) + geom_point(alpha=0.3))
with(df,plot(x,y,col="#00000020"))

#make this a data frame? How to bin the data according to soil and veg type?
# data frame of CMRSET/rechNet and veg Soil Combo number?
# extract vectors with the same veg/soil combo number? This seems more sensible.

# first combine the key to just veg and soil.

keyVector <- as.vector(rasterKey)
climate <- floor(keyVector/100)
soil <- floor((keyVector-climate*100)/10)
veg <- (keyVector-climate*100-soil*10)
vegSoil <- soil*10+veg
uniqueVegSoil <- unique(vegSoil)
uniqueVegSoil <- uniqueVegSoil[-1] # This may not work for other data sets
uniqueVegSoil <- sort(uniqueVegSoil, decreasing = FALSE)

```

```

rasterClimate <- floor(rasterKey/100)
rasterSoil <- floor((rasterKey-rasterClimate*100)/10)
rasterVeg <- rasterKey-rasterClimate*100-rasterSoil*10
plot(rasterSoil)
#plot(dtw, zlim = c(0,50))

#Define groundwater depth colour

gwDepthIndicator <- ifelse (depth<0,0, ifelse (depth<=2,1,ifelse(depth<=4,2,
      ifelse(depth<=6,3, ifelse(depth<=10,4,5))))))

par(mfrow = c(3,3))
#Par(mfrow = c(1,1))

pdf(file = paste(fpath,"WAVES_CMRSSET_calibration2.pdf",sep = ""))
cbPalette <- c("#999999", "#E69F00", "#56B4E9", "#009E73", "#F0E442", "#0072B2", "#D55E00",
"#CC79A7")

# Scatter plot for each soil and veg combination (63)

#x <- 34
for (x in uniqueVegSoil) {
  # pick out xData[x], yData[x]
  list <- which(vegSoil==x)
  xData <- as.vector(CMRSET[list])
  yData <- as.vector(rechNet[list])
  gwDI <- gwDepthIndicator[list]
  # plot out a 7 x 9 lattice of scatter plots.
  # plotlist[x] <- print(qplot(xData, yData,col="#00000020", main = x,
  # qplot(xData, yData,col="#00000020", main = x,
  print(qplot(xData, yData, main = x, colour=gwDI,palette=cbPalette, alpha = I(1/5),
  xlab = "CMRSSET Net R (mm/y)", ylab = "Waves Net R (mm/y)",
  xlim=c(-600, 600), ylim=c(-600, 600)))

}

dev.off()

# Box plots of depth vs net R for each land use type, boxes for every metre depth.

#Switch to select for climate zone

#rechNet <- rechNet[which(rasterClimate==8)]

#Beachport 1
#BorderTown 2

```

```

#CapeNorth    3
#Dartmoor     4
#Edenhope     5
#Goroke       6
#Kingston     7
#Lucindale    8
#MtBurr       9
#MtGamb      10
#Naracoorte  11
#Penola      12

```

```

# And continue on...
# Assign depths into boxes

```

```

boxCropsnetR <- rechNet[which(veg==1)] # check this is correct
boxPerennetR <- rechNet[which(veg==2)]
boxNativenetR <- rechNet[which(veg==3)]
boxSoftWnetR <- rechNet[which(veg==4)]
boxHardWnetR <- rechNet[which(veg==6)]

```

```

soilCrops <- soil[which(veg==1)]
soilPeren <- soil[which(veg==2)]
soilNative <- soil[which(veg==3)]
soilSoftW <- soil[which(veg==4)]
soilHardW <- soil[which(veg==6)]

```

```

#????
climateCrops <- climate[which(veg==1)]
climatePeren <- climate[which(veg==2)]
climateNative <- climate[which(veg==3)]
climateSoftW <- climate[which(veg==4)]
climateHardW <- climate[which(veg==6)]

```

```

boxCropsCMRSET <- as.vector(CMRSET[which(veg==1)]) # check this is correct
boxPerenCMRSET <- as.vector(CMRSET[which(veg==2)])
boxNativeCMRSET <- as.vector(CMRSET[which(veg==3)])
boxSoftWCMRSET <- as.vector(CMRSET[which(veg==4)])
boxHardWCMRSET <- as.vector(CMRSET[which(veg==6)])

```

```

#get rid of <=0 and >30
#separate into 1m boxes

```

```

boxCropsdepth<-depth[which(veg==1)]
boxCropsdepth[boxCropsdepth[]<0.5]<-NA
boxCropsdepth[boxCropsdepth[]>30.5]<-NA
boxCropsdepth <- round(boxCropsdepth)

```

```

boxPerendepth<-depth[which(veg==2)]
boxPerendepth[boxPerendepth[]<0.5]<-NA
boxPerendepth[boxPerendepth[]>30.5]<-NA
boxPerendepth <- round(boxPerendepth)

```

```

boxNativeDepth<-depth[which(veg==3)]
boxNativeDepth[boxNativeDepth[]<0.5]<-NA
boxNativeDepth[boxNativeDepth[]>30.5]<-NA
boxNativeDepth <- round(boxNativeDepth)

boxSoftWDepth<-depth[which(veg==4)]
boxSoftWDepth[boxSoftWDepth[]<0.5]<-NA
boxSoftWDepth[boxSoftWDepth[]>30.5]<-NA
boxSoftWDepth <- round(boxSoftWDepth)

boxHardWDepth<-depth[which(veg==6)]
boxHardWDepth[boxHardWDepth[]<0.5]<-NA
boxHardWDepth[boxHardWDepth[]>30.5]<-NA
boxHardWDepth <- round(boxHardWDepth)

dfCrops <- data.frame(boxCropsnetR,boxCropsDepth,boxCropsCMRSET)
dfPeren <- data.frame(boxPerennetR,boxPerenDepth,boxPerenCMRSET)
dfNative <- data.frame(boxNativenetR,boxNativeDepth,boxNativeCMRSET)
dfSoftW <- data.frame(boxSoftWnetR,boxSoftWDepth,boxSoftWCMRSET)
dfHardW <- data.frame(boxHardWnetR,boxHardWDepth,boxHardWCMRSET)

par(mfrow = c(2,3))

# Box plots grouped by land use type

boxplot(boxCropsnetR~boxCropsDepth,data=dfCrops, main="Modelled net R from cropped areas",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
        # axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
        # pars = list(boxwex = 0.6,
        # staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
        # cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))

boxplot(boxPerennetR~boxPerenDepth,data=dfPeren, main="Modelled net R from perennially cropped
areas",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
        # axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
        # pars = list(boxwex = 0.6,
        # staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
        # cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxNativenetR~boxNativeDepth,data=dfNative, main="Modelled net R from native vegetation",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
        # axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
        # pars = list(boxwex = 0.6,
        # staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
        # cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

```

boxplot(boxSoftWnetR~boxSoftWdepth,data=dfSoftW, main="Modelled net R from softwood plantations",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
#             staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
#             cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

```

boxplot(boxHardWnetR~boxHardWdepth,data=dfHardW, main="Modelled net R from hardwood
plantations",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
#             staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
#             cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

# CMRSET data

```

boxplot(boxCropsCMRSET~boxCropsdepth,data=dfCrops, main="CMRSET net R from cropped areas",
        xlab="Depth to groundwater (m)",
        ylab="CMRSET net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
#             staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
#             cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

```

boxplot(boxPerenCMRSET~boxPerendepth,data=dfPeren, main="CMRSET net R from perennially cropped
areas",
        xlab="Depth to groundwater (m)",
        ylab="CMRSET net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
#             staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
#             cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

```

boxplot(boxNativeCMRSET~boxNativedepth,data=dfNative, main="CMRSET net R from native vegetation",
        xlab="Depth to groundwater (m)",
        ylab="CMRSET net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
#             staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
#             cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

```

boxplot(boxSoftWCMRSET~boxSoftWdepth,data=dfSoftW, main="CMRSET net R from softwood
plantations",
        xlab="Depth to groundwater (m)",

```



```

      ylab="CMRSET net R (mm/a)", ylim=c(-500,400))#,
#   axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
#   pars = list(boxwex = 0.6,
#               staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
#               cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxHardWCMRSET~boxHardWdepth,data=dfHardW, main="CMRSET net R from hardwood
plantations",
      xlab="Depth to groundwater (m)",
      ylab="CMRSET net R (mm/a)", ylim=c(-500,400))#,
#   axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
#   pars = list(boxwex = 0.6,
#               staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
#               cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

```

# Box plots of depth vs soil type for Veg types
# Crops

```

```

#boxS1netR <- boxCropsnetR[which(soilCrops==1)] # check this is correct
#boxS2netR <- boxCropsnetR[which(soilCrops==2)]
#boxS3netR <- boxCropsnetR[which(soilCrops==3)]
#boxS4netR <- boxCropsnetR[which(soilCrops==4)]
#boxS5netR <- boxCropsnetR[which(soilCrops==5)]
#boxS6netR <- boxCropsnetR[which(soilCrops==6)]
#boxS7netR <- boxCropsnetR[which(soilCrops==7)]

```

```

#boxS1CMRSET <- boxCropsCMRSET[which(soilCrops==1)] # check this is correct
#boxS2CMRSET <- boxCropsCMRSET[which(soilCrops==2)]
#boxS3CMRSET <- boxCropsCMRSET[which(soilCrops==3)]
#boxS4CMRSET <- boxCropsCMRSET[which(soilCrops==4)]
#boxS5CMRSET <- boxCropsCMRSET[which(soilCrops==5)]
#boxS6CMRSET <- boxCropsCMRSET[which(soilCrops==6)]
#boxS7CMRSET <- boxCropsCMRSET[which(soilCrops==7)]

```

```

#boxS1depth <- boxCropsdepth[which(soilCrops==1)] # check this is correct
#boxS2depth <- boxCropsdepth[which(soilCrops==2)]
#boxS3depth <- boxCropsdepth[which(soilCrops==3)]
#boxS4depth <- boxCropsdepth[which(soilCrops==4)]
#boxS5depth <- boxCropsdepth[which(soilCrops==5)]
#boxS6depth <- boxCropsdepth[which(soilCrops==6)]
#boxS7depth <- boxCropsdepth[which(soilCrops==7)]

```

```

#Perennial

```

```

#boxS1netR <- boxPerennetR[which(soilPeren==1)] # check this is correct
#boxS2netR <- boxPerennetR[which(soilPeren==2)]
#boxS3netR <- boxPerennetR[which(soilPeren==3)]
#boxS4netR <- boxPerennetR[which(soilPeren==4)]
#boxS5netR <- boxPerennetR[which(soilPeren==5)]

```

```

#boxS6netR <- boxPerennetR[which(soilPeren==6)]
#boxS7netR <- boxPerennetR[which(soilPeren==7)]

#boxS1CMRSET <- boxPerenCMRSET[which(soilPeren==1)] # check this is correct
#boxS2CMRSET <- boxPerenCMRSET[which(soilPeren==2)]
#boxS3CMRSET <- boxPerenCMRSET[which(soilPeren==3)]
#boxS4CMRSET <- boxPerenCMRSET[which(soilPeren==4)]
#boxS5CMRSET <- boxPerenCMRSET[which(soilPeren==5)]
#boxS6CMRSET <- boxPerenCMRSET[which(soilPeren==6)]
#boxS7CMRSET <- boxPerenCMRSET[which(soilPeren==7)]

#boxS1depth <- boxPerendepth[which(soil==1)] # check this is correct
#boxS2depth <- boxPerendepth[which(soil==2)]
#boxS3depth <- boxPerendepth[which(soil==3)]
#boxS4depth <- boxPerendepth[which(soil==4)]
#boxS5depth <- boxPerendepth[which(soil==5)]
#boxS6depth <- boxPerendepth[which(soil==6)]
#boxS7depth <- boxPerendepth[which(soil==7)]

#Native

# boxS1netR <- boxNativenetR[which(soilNative==1)] # check this is correct
# boxS2netR <- boxNativenetR[which(soilNative==2)]
# boxS3netR <- boxNativenetR[which(soilNative==3)]
# boxS4netR <- boxNativenetR[which(soilNative==4)]
# boxS5netR <- boxNativenetR[which(soilNative==5)]
# boxS6netR <- boxNativenetR[which(soilNative==6)]
# boxS7netR <- boxNativenetR[which(soilNative==7)]
#
# boxS1CMRSET <- boxNativeCMRSET[which(soilNative==1)] # check this is correct
# boxS2CMRSET <- boxNativeCMRSET[which(soilNative==2)]
# boxS3CMRSET <- boxNativeCMRSET[which(soilNative==3)]
# boxS4CMRSET <- boxNativeCMRSET[which(soilNative==4)]
# boxS5CMRSET <- boxNativeCMRSET[which(soilNative==5)]
# boxS6CMRSET <- boxNativeCMRSET[which(soilNative==6)]
# boxS7CMRSET <- boxNativeCMRSET[which(soilNative==7)]
#
# boxS1depth <- boxNatedepth[which(soilNative==1)] # check this is correct
# boxS2depth <- boxNatedepth[which(soilNative==2)]
# boxS3depth <- boxNatedepth[which(soilNative==3)]
# boxS4depth <- boxNatedepth[which(soilNative==4)]
# boxS5depth <- boxNatedepth[which(soilNative==5)]
# boxS6depth <- boxNatedepth[which(soilNative==6)]
# boxS7depth <- boxNatedepth[which(soilNative==7)]

#Softwood

boxS1netR <- boxSoftWnetR[which(soilSoftW==1)] # check this is correct
boxS2netR <- boxSoftWnetR[which(soilSoftW==2)]
boxS3netR <- boxSoftWnetR[which(soilSoftW==3)]
boxS4netR <- boxSoftWnetR[which(soilSoftW==4)]
boxS5netR <- boxSoftWnetR[which(soilSoftW==5)]
boxS6netR <- boxSoftWnetR[which(soilSoftW==6)]
boxS7netR <- boxSoftWnetR[which(soilSoftW==7)]

```

```

boxS1CMRSET <- boxSoftWCMRSET[which(soilSoftW==1)] # check this is correct
boxS2CMRSET <- boxSoftWCMRSET[which(soilSoftW==2)]
boxS3CMRSET <- boxSoftWCMRSET[which(soilSoftW==3)]
boxS4CMRSET <- boxSoftWCMRSET[which(soilSoftW==4)]
boxS5CMRSET <- boxSoftWCMRSET[which(soilSoftW==5)]
boxS6CMRSET <- boxSoftWCMRSET[which(soilSoftW==6)]
boxS7CMRSET <- boxSoftWCMRSET[which(soilSoftW==7)]

```

```

boxS1depth <- boxSoftWdepth[which(soilSoftW==1)] # check this is correct
boxS2depth <- boxSoftWdepth[which(soilSoftW==2)]
boxS3depth <- boxSoftWdepth[which(soilSoftW==3)]
boxS4depth <- boxSoftWdepth[which(soilSoftW==4)]
boxS5depth <- boxSoftWdepth[which(soilSoftW==5)]
boxS6depth <- boxSoftWdepth[which(soilSoftW==6)]
boxS7depth <- boxSoftWdepth[which(soilSoftW==7)]

```

# Hardwood

```

#boxS1netR <- boxHardWnetR[which(soilHardW==1)] # check this is correct
#boxS2netR <- boxHardWnetR[which(soilHardW==2)]
#boxS3netR <- boxHardWnetR[which(soilHardW==3)]
#boxS4netR <- boxHardWnetR[which(soilHardW==4)]
#boxS5netR <- boxHardWnetR[which(soilHardW==5)]
#boxS6netR <- boxHardWnetR[which(soilHardW==6)]
#boxS7netR <- boxHardWnetR[which(soilHardW==7)]

```

```

#boxS1CMRSET <- boxHardWCMRSET[which(soilHardW==1)] # check this is correct
#boxS2CMRSET <- boxHardWCMRSET[which(soilHardW==2)]
#boxS3CMRSET <- boxHardWCMRSET[which(soilHardW==3)]
#boxS4CMRSET <- boxHardWCMRSET[which(soilHardW==4)]
#boxS5CMRSET <- boxHardWCMRSET[which(soilHardW==5)]
#boxS6CMRSET <- boxHardWCMRSET[which(soilHardW==6)]
#boxS7CMRSET <- boxHardWCMRSET[which(soilHardW==7)]

```

```

#boxS1depth <- boxHardWdepth[which(soilHardW==1)] # check this is correct
#boxS2depth <- boxHardWdepth[which(soilHardW==2)]
#boxS3depth <- boxHardWdepth[which(soilHardW==3)]
#boxS4depth <- boxHardWdepth[which(soilHardW==4)]
#boxS5depth <- boxHardWdepth[which(soilHardW==5)]
#boxS6depth <- boxHardWdepth[which(soilHardW==6)]
#boxS7depth <- boxHardWdepth[which(soilHardW==7)]

```

# this is the same no matter which land use type is used.

```

boxS1resid <- boxS1CMRSET - boxS1netR
boxS2resid <- boxS2CMRSET - boxS2netR
boxS3resid <- boxS3CMRSET - boxS3netR
boxS4resid <- boxS4CMRSET - boxS4netR
boxS5resid <- boxS5CMRSET - boxS5netR
boxS6resid <- boxS6CMRSET - boxS6netR
boxS7resid <- boxS7CMRSET - boxS7netR

```

```

dfS1 <- na.omit(data.frame(boxS1netR,boxS1depth,boxS1CMRSET, boxS1resid))

```

```

dfS2 <- na.omit(data.frame(boxS2netR,boxS2depth,boxS2CMRSET, boxS2resid))
dfS3 <- na.omit(data.frame(boxS3netR,boxS3depth,boxS3CMRSET, boxS3resid))
dfS4 <- na.omit(data.frame(boxS4netR,boxS4depth,boxS4CMRSET, boxS4resid))
dfS5 <- na.omit(data.frame(boxS5netR,boxS5depth,boxS5CMRSET, boxS5resid))
dfS6 <- na.omit(data.frame(boxS6netR,boxS6depth,boxS6CMRSET, boxS6resid))
dfS7 <- na.omit(data.frame(boxS7netR,boxS7depth,boxS7CMRSET, boxS7resid))

# Box plots grouped by soil type
par(mfrow = c(2,4))

boxplot(boxS1netR~boxS1depth,data=dfS1, main="Modelled net R from Soil type 1",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS2netR~boxS2depth,data=dfS2, main="Modelled net R from Soil type 2",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS3netR~boxS3depth,data=dfS3, main="Modelled net R from Soil type 3",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS4netR~boxS4depth,data=dfS4, main="Modelled net R from Soil type 4",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS5netR~boxS5depth,data=dfS5, main="Modelled net R from Soil type 5",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

```

boxplot(boxS6netR~boxS6depth,data=dfS6, main="Modelled net R from Soil type 6",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS7netR~boxS7depth,data=dfS7, main="Modelled net R from Soil type 7",
        xlab="Depth to groundwater (m)",
        ylab="WAVES net R (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

#dev.off()

# CMRSET data
par(mfrow = c(2,4))
boxplot(boxS1CMRSET~boxS1depth,data=dfS1, main="CMRSET net R from Soil type 1",
        at=c(1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30),
        xlab="Depth to groundwater (m)",
        ylab="CMRSET net R (mm/a)", ylim=c(-200,200))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS2CMRSET~boxS2depth,data=dfS2, main="CMRSET net R from Soil type 2",
        xlab="Depth to groundwater (m)",
        ylab="CMRSET net R (mm/a)", ylim=c(-200,200))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS3CMRSET~boxS3depth,data=dfS3, main="CMRSET net R from Soil type 3",
        xlab="Depth to groundwater (m)",
        ylab="CMRSET net R (mm/a)", ylim=c(-200,200))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS4CMRSET~boxS4depth,data=dfS4, main="CMRSET net R from Soil type 4",
        xlab="Depth to groundwater (m)",

```

```

      ylab="CMRSET net R (mm/a)", ylim=c(-200,200))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(box$5CMRSET~box$5depth,data=df$5, main="CMRSET net R from Soil type 5",
      xlab="Depth to groundwater (m)",
      ylab="CMRSET net R (mm/a)", ylim=c(-200,200))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(box$6CMRSET~box$6depth,data=df$6, main="CMRSET net R from Soil type 6",
      xlab="Depth to groundwater (m)",
      ylab="CMRSET net R (mm/a)", ylim=c(-200,200))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(box$7CMRSET~box$7depth,data=df$7, main="CMRSET net R from Soil type 7",
      xlab="Depth to groundwater (m)",
      ylab="CMRSET net R (mm/a)", ylim=c(-200,200))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

#plot 'n'

#Soil 3
#xax <- unique(na.omit(box$1depth))
#yax <- nrow(na.omit(box$1depth))

#yuck

# Box plots grouped by soil type of residuals
par(mfrow = c(2,4))

boxplot(box$1resid~box$1depth,data=df$1, main="Net R residuals R from Soil type 1",
      xlab="Depth to groundwater (m)",
      ylab="Net R residuals (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```

```

boxplot(boxS2resid~boxS2depth,data=dfS2, main="Net R residuals from Soil type 2",
        xlab="Depth to groundwater (m)",
        ylab="Net R residuals (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS3resid~boxS3depth,data=dfS3, main="Net R residuals from Soil type 3",
        xlab="Depth to groundwater (m)",
        ylab="Net R residuals (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS4resid~boxS4depth,data=dfS4, main="Net R residuals from Soil type 4",
        xlab="Depth to groundwater (m)",
        ylab="Net R residuals (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS5resid~boxS5depth,data=dfS5, main="Net R residuals from Soil type 5",
        xlab="Depth to groundwater (m)",
        ylab="Net R residuals (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS6resid~boxS6depth,data=dfS6, main="Net R residuals from Soil type 6",
        xlab="Depth to groundwater (m)",
        ylab="Net R residuals (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

boxplot(boxS7resid~boxS7depth,data=dfS7, main="Net R residuals from Soil type 7",
        xlab="Depth to groundwater (m)",
        ylab="Net R residuals (mm/a)", ylim=c(-500,400))#,
# axis(1, lwd = 2.0), axis(2, lwd = 2.0), axis(3, lwd = 2.0), axis(4, lwd = 2.0),
# pars = list(boxwex = 0.6,
# staplewex = 0.8, outwex = 1.0, cex = 1.5, cex.lab = 1.5, cex.main = 1.5,
# cex.axis = 1.5, cex.sub = 1.5, lwd = 1, mar = c(8, 6, 6, 4) + 2))
abline(h=(seq(-500,400,50)), col="lightgray", lty="dotted")

```



# Residuals vs depth for each soil veg combo

# Relative residuals vs depth for each soil veg combo

# Is there any way to translate this to how much we should change the WAVES data by?

## Appendix D Depth to water table vs net recharge curves







Government  
of South Australia

Department of Environment,  
Water and Natural Resources



THE UNIVERSITY  
of ADELAIDE



University of  
South Australia



Flinders  
UNIVERSITY  
ADELAIDE • AUSTRALIA

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Water, CSIRO, Flinders University, the University of Adelaide and the University of South Australia.