Government of **Western Australia**
Department of **Water**

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Perth Regional Aquifer Modelling System (PRAMS) model development

A vertical flux model for the Perth groundwater region

Hydrogeological record series

Report no. HG33
June 2009

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Summary

The Water Corporation and the Department of Water have developed a coupled recharge and groundwater model – PRAMS – to aid management of the regional groundwater system around the Perth coastal area. The Water Corporation engaged CSIRO to develop the vertical flux model (VFM) component for PRAMS. The new model has improved biophysical representation: it enables better prediction of the impacts of managed withdrawal from the aquifers, particularly impacts on native vegetation and especially wetlands and phreatophytic ecosystems. The model also gives a better understanding of the effects of various land uses on the regional groundwater resource, and permits modelling of scenarios for vegetation management that may enhance or deplete the available water resource.

The new model is a combination of three components: a model of the saturated groundwater based on MODFLOW, the VFM, and a geographic information system (GIS) that controls data management for the model. The VFM is the interface between the MODFLOW model and a selection of recharge models, of which WAVES is one, and replaces the functions of the two MODFLOW packages RCH and EVT.

The VFM calculates vertical net flux (recharge or discharge) to the saturated aquifer, and MODFLOW calculates the regional horizontal flow due to this vertical flux and other groundwater flow sources and sinks. The VFM solves vertical flow only for subregions of the MODFLOW model. These subregions consist of representative recharge units (RRU) covering from one to several thousand MODFLOW cells that are grouped based on depth to watertable, rainfall, land use, soil and vegetation characteristics.

The VFM performs four key tasks:

- manages the spatial selection of which recharge model to run in each cell of the model domain
- manages data input to the recharge models
- runs the recharge models
- passes the calculated recharge back to MODFLOW for each cell.

TTo calculate recharge under pasture, pine plantations and native bushland, a biophysical model (WAVES) is used. WAVES accounts for antecedent moisture conditions in the root zone and deep unsaturated zone for different vegetation groups, extent of plant development, root-zone depth, and the physical characteristics of soil type (soil-moisture characteristics). In addition to WAVES, the VFM also provides more computationally efficient algorithms to calculate net recharge to the aquifer for:

- areas that are managed with respect to the application of water, such as market gardens, golf courses and large parks and reserves
- highly urbanised areas, where rainfall is directed to ground below the predominant root-zone depth from impervious surfaces such as houses, roads and parking lots.

The recharge models are run on daily time steps, with net recharge accumulated through a run accumulated and passed to MODFLOW for each MODFLOW time step. Net recharge and watertable position are then determined for each MODFLOW stress period (nominally one month, but could be any length).

Data are required as spatially distributed land use, including vegetation classification and leaf area index (LAI), climate domain, soil classification and watertable depth. For each RRU on which WAVES is to be run, soil-moisture characteristics and vegetation parameters are required; for the other RRUs urban and irrigation model parameters are needed. Also required are daily climate data series for each climate domain and temporal land-use series across the domain (currently in two-year intervals).

The new model, with its improved biophysical representation, allows a much more robust test of our understanding of the processes controlling recharge. The processes, fluxes and state variables are more clearly related to measurable quantities in the field and thus may be more easily tested against data. The model also gives a more robust tool to assess future management scenarios of the groundwater resource.

Sensitivity analysis found that in the long term, mean annual groundwater recharge is strongly correlated with mean annual rainfall, despite individual years showing significant discrepancies. Where the depth to watertable is shallow, annual recharge is strongly correlated with annual rainfall. However, where the depth to watertable is large, the correlation between annual rainfall and annual recharge is very poor owing to the delay in the recharge response. Analysis indicates that estimates of groundwater recharge are very sensitive to light extinction coefficient, LAI, the maximum rooting depth and the root distribution of the vegetation. Recharge is moderately sensitive to the vegetation parameters of maximum carbon assimilation rate, slope of the conductance and rainfall interception, and the soil water-holding capacity and hydraulic conductivity. However, there are strong correlations between the root distribution and soil hydraulic characteristics that influence recharge quantity and timing.

New data are required to test the model’s performance (particularly vertical flux rate) for different soils, and to establish the field-scale flux rate, rather than a point measurement. Data are required to determine the vegetation’s ability to take water from the watertable, and how this varies with depth and time as the watertable fluctuates. The latter is critical for management of both pines and native vegetation, as this interaction will define the sensitivity of both these vegetation types to lowering or raising of the watertable. It will also affect the optimisation of pine plantation growth against water use. In addition, it is essential to establish the LAI at which pines use all the rainfall, and whether this varies with age or stem density. The most robust method to determine recharge on a vegetation-community scale would be to calculate rainfall and measure evapotranspiration using an atmospheric flux station. A number of follow-up field investigation programs are in progress or proposed to fill the gaps identified.

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Much of the sensitivity analysis and soil-model characterisation work covered in this report has been undertaken by Dr Chengchao Xu of the Water Corporation, without which this project would not have reached its current status.

1 Introduction

This report discusses the development and operation of a coupled recharge model to aid management of the regional groundwater system around the Perth coastal area. The Water Corporation and the Department of Water (formerly Water and Rivers Commission) reviewed the Perth Urban Water Balance Study (PUWBS) model, and determined that an enhanced capability to model recharge and groundwater flow was necessary to underpin planning and management decisions. As a result, these agencies, with CSIRO Land and Water and CyMod Systems, have developed a new groundwater modelling system for the Perth region. The system consists of three major components: a GIS-based data management system, a saturated-flow model, and an unsaturated-zone vertical flux model (VFM). These components have been developed in parallel and are integrated. Calibration and validation are now complete. The project was conducted under the auspices of the Centre for Groundwater Studies as a Member Project.

The new model replaces one developed in the 1980s – the PUWBS (Cargeeg et al. 1987) – and capitalises on recent developments in biophysical understanding and modelling, and the greater computing power now available. The new biophysical representation enables better prediction of the impacts of managed withdrawal from the aquifers in the Perth region, particularly impacts on native vegetation and especially wetlands and phreatophytic ecosystems. The model also gives a better understanding of the effects of various land uses on the regional groundwater resource, and permits modelling of scenarios for pine plantation management that may enhance or deplete the available water resource.

This report presents the main details and a summary of the working algorithms of the VFM (the component that manages the vertical water flux in the unsaturated zone). All details are given in companion documents by Barr et al. (2002) and Canci et al. (2003).

The Water Corporation engaged CSIRO to develop the VFM after commissioning a study on conceptual models of recharge processes on the Swan coastal plain (Townley 2000). In Phase 1 of this study, the WAVES model was evaluated for potential use for vertical flux estimation. Results from applying the model to a combination of land use, soil type and watertable depth showed the model performed well in most of the cases tested compared with field measurements. It was recommended that the WAVES model be adopted as the platform for the VFM in the new groundwater modelling system. It was also recommended that to fully evaluate the suitability of the WAVES model in a three-dimensional modelling system, a small-scale application of MODFLOW (McDonald & Harbaugh 1988) linked to WAVES undergo testing before full-scale application.

The work described in this report was developed by CSIRO. The Water Corporation and CyMod have applied the work to a pilot study to test the MODFLOW-VFM linkage.

2 Project Design

The project's aim was to develop a computer software tool to manage the calculation of recharge across the domain and pass this on a cell-by-cell basis to the saturated groundwater model. The Department of Water constructed the saturated aquifer model using MODFLOW: it was then calibrated independently before coupling to the VFM.

The project has been managed in four phases.

Phase 1: Evaluation of the one-dimensional model WAVES as a suitable tool to calculate the vertical unsaturated soil-moisture fluxes and evaporation.

Following the conclusion that WAVES was suitable and necessary for the task at hand, the project continued:

Phase 2: Development of the VFM to manage the data flow and computation of recharge and groundwater discharge to the atmosphere.

Phase 3 Data assembly, calibration and testing of the coupled model on a pilot area.

Phase 4: Assembly of data and application to the full domain.

3 Model Description

The new model is a combination of three components: a 12-layer MODFLOW model of the saturated groundwater, the VFM, and a GIS that controls data management for the model. The VFM is the interface between the MODFLOW model and a selection of recharge models, replacing the functions of the two MODFLOW packages RCH and EVT. The VFM-MODFLOW linkage is a computationally efficient coupling between the simulation of net vertical flux (recharge) to the saturated aquifer, and the MODFLOW calculation of the regional horizontal flow due to this vertical flux and other groundwater flow sources and sinks. The VFM also manages the assembly of input data and selection of the required recharge and evaporation model.

Where possible (subject to land use), the new model uses a more sophisticated biophysical model (WAVES) to simulate vertical water flow through soil as well as water uptake by vegetation. WAVES, developed by CSIRO and now in the public domain (Zhang & Dawes 1998), is described in detail in the Phase 1 report for this project (Hatton et al. 2001).

In some cells the use of WAVES is inappropriate. This may be because the watertable is above or close to the ground surface (e.g. lakes and wetlands) or because anthropogenic factors govern the recharge (e.g. market gardens, urban areas). The VFM provides alternative and more computationally efficient algorithms to calculate net recharge to the aquifer for:

- areas that are managed with respect to the application of water, such as market gardens, golf courses and large parks and reserves
- highly urbanised areas, where rainfall is directed to ground below the predominant root-zone depth from impervious surfaces such as houses, roads and parking lots.

3.1 VFM–MODFLOW linkage

The VFM (Figure 1) calculates recharge and discharge from the aquifer system and passes this to the aquifer model. The VFM performs four key tasks:

- manages the spatial selection of which recharge model to run in each cell of the model domain
- manages data input to the recharge models
- runs the recharge models
- passes the calculated recharge back to MODFLOW for each cell.

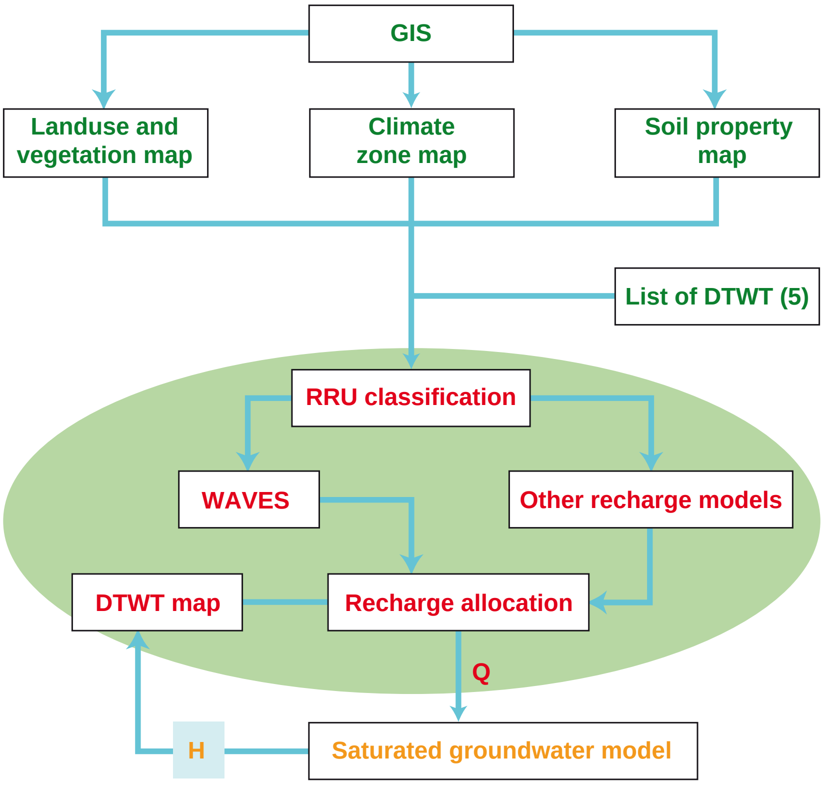

Figure 1 Schematic of the vertical flux model (VFM) linkage to MODFLOW, showing the disaggregation of the domain into representative recharge units (RRU), and the cycling between recharge/discharge (vertical flux) and watertable-surface calculations. (H = piezometric head surface, Q = spatially distributed vertical flux to saturated model, DTWT = depth to watertable.)

The recharge models are run on daily time steps, with net recharge accumulated through a run covering each MODFLOW time step (nominally one month, but could be any length). The total recharge is passed as a recharge rate to MODFLOW for each time step. At the end of each stress period, the VFM stores the recharge model conditions to use as the initial conditions for the recharge calculations of the next stress period. Computed recharge passed to MODFLOW may be positive or negative (uptake from the watertable).

The MODFLOW saturated-zone model is run as a normal MODFLOW run, with the exception that some subprogram cells have been modified to use the VFM and to facilitate the passing of information to the VFM.

Representative recharge units

Initially it was proposed to use a recharge simulation for each cell of PRAMS; however, it was clear that the time needed for a single simulation would be prohibitive. Hence, the VFM solves vertical flow only for subregions of the MODFLOW model. These subregions, known as representative recharge units (RRU) – consist of one up to several thousand MODFLOW cells grouped on the basis of the environmental characteristics that control recharge to the groundwater. Currently four attributes are used, but in principle there is no fixed set of criteria, and in future some may be added or subtracted. To create these RRUs, the four factors identified as controlling the recharge and evapotranspiration are:

- the land use, which includes the type and density of vegetation
- the climate
- the soil profile
- the depth to the watertable.

The number of recharge simulations required is the number of combinations of attributes leading to unique RRUs: currently there are hundreds, although it is likely the number of RRUs will rise to about 1000 in actual operation. In most of the applications to date there have been 13 vegetation/land-use classes, six climate classes, six soil classes and eight depth-to-watertable classes, leading to a total of 3744 possible RRU combinations. In practice, however, only about 700 combinations actually occur and these are the RRUs used in the simulations.

WAVES — one-dimensional soil-water atmosphere transfer model

WAVES is a one-dimensional daily time-step model that simulates the fluxes of water and energy between the atmosphere, vegetation and soil systems. It is a process-based model that couples these systems by modelling the interactions and feedback between them. WAVES attempts to model each subsystem with a consistent level of detail, so that no area is over emphasised or requires too many parameters, and similarly no area is treated in a trivial manner. More than this, WAVES tries to strike a balance between the complexity of the model as a whole, the usefulness of the model and its ease of use, and the accuracy of the model outputs (Zhang & Dawes 1998).

WAVES accounts for antecedent moisture conditions in the root zone and deep unsaturated zone for different plant species, extent of plant development, root-zone depth, and the physical characteristics of soil type (soil-moisture characteristics).

To simplify the WAVES simulations in this application, a number of options are not currently used – solute (salt) transport, vegetation growth, grazing and surface flooding – and the model has been limited to a single layer of vegetation. These options may be available in later versions of the VFM. Because the first three attributes outlined above (land use, climate and soil) are fixed for each period according to the user’s input, it is convenient to describe a preliminary RRU or pre-RRU that is a combination of the three factors. It can be represented by a six-digit code – *LUCLSP* – where:

- *LU* is the two-digit code for the land use
- *CL* is the two-digit code for the climate zone
- *SP* is the two-digit code for the soil profile.

WAVES simulations are run for each pre-RRU at a predefined set of groundwater depths. The depth is indicated with another two-digit numerical code – *WT* – giving the full RRU designation *WTLUCLSP*. The recharge for each cell is calculated from the set of WAVES simulations for the cell's pre-RRU and based on the depth to the watertable in the cell.

Non-WAVES recharge models

A number of land uses do not warrant the detail of a WAVES simulation, either because the data are not available, or because they are subject to significant management intervention that makes biophysical representation very difficult. The user can select an alternative set of models in either the land-use RRU file for specified non-WAVES models or in the defaults file when the watertable is close to the surface. These special cases have a modified interception algorithm, having one or two parameters that account for losses and the percentage of rainfall reaching the ground.

The first model uses a constant multiplier for the rainfall and potential evaporation to calculate the recharge. This can be expressed in equation form as:

$$R_{i,j} = RNMLT_{i,j} * RN_{i,j} - EVMLT_{i,j} * RN_{i,j} \qquad (1)$$

where $R_{i,j}$ is the rate of recharge per unit surface area of watertable in cell *i,j*; $RNMLT_{i,j}$ is a non-dimensional multiplier for the rainfall in that cell; $RN_{i,j}$ is the rainfall per unit surface area per unit time; $EVMLT_{i,j}$ is the non-dimensional multiplier for the evaporation; and $EV_{i,j}$ is the potential evaporation per unit surface area per unit time.

The second model is more complex, being based on a piece-wise linear relationship about critical watertable depths. The lowest critical watertable depth is a cut-off depth, underneath which the multipliers for the climate data are constant. This lower point corresponds to the extinction depth used in the evapotranspiration module (EVT) in MODFLOW. Between critical depths, the multiplier varies linearly. There is no rainfall infiltration algorithm; recharge and discharge are applied directly to the watertable. Details are given in the manual (Barr et al. 2002).

VFM–MODFLOW linkage

The VFM is coupled in real time to MODFLOW, replacing the existing EVT module, as defined in MODFLOW 96. The recharge/discharge VFM algorithm is implemented as a subroutine that takes inputs from model data files describing land use, extent of vegetation cover and vegetation type, and climatic data (rainfall, temperature etc.). The subroutine calculates the following:

- interception
- the water removed from the root zone
- storage in the unsaturated zone
- the resulting net flux to, or uptake from, the aquifer.

4 Program operation

The VFM is intended to be an integral part of the PRAMS framework, not a standalone program. Yet it can be run separately, and this facilitates testing and calibration. To operate the model, a number of steps are required:

1. Data assembly – GIS, static, and time series and initialisation data
2. Assemble VFM input-control files
3. Initialise and run

4.1 Data assembly

The data may be loosely broken into a number of categories:

- GIS data – land use including vegetation classification and leaf area index (LAI), climate domain, soil classification and watertable depth. All of these are static for a cell except watertable depth, which is updated each MODFLOW time step (nominally one month, but may vary).
- other static data – soil-moisture characteristics, vegetation parameters, urban and irrigation model parameters.
- temporal data – daily climate data series for each climate domain, land-use series across the domain (currently expected in two-year intervals).

The details of data assembly and required format are given in the companion manual documentation (Barr et al. 2003; Canci et al. 2003; Xu et al. 2004).

The VFM currently recognises the following land uses:

- pine plantation
- native bushland
- pasture or dryland agriculture
- irrigated horticulture and parkland
- wetlands, lakes and swamps
- urban and industrial (made up of largely impervious surfaces).

The first three of these are classified as WAVES-type for the VFM and recharge is calculated using WAVES; simpler models are used for the others. Soil-moisture characteristics and soil-profile ‘nodes’ files must be determined beforehand and stored in files accessible to the program at run-time. The same is required for the vegetation parameters. The spatially distributed data use standard MODFLOW files for their distribution, and any updates that occur through a simulation use standard MODFLOW files to pass this information.

4.2 Assemble VFM input-control files

The VFM's input-control data are stored in files that typically list other source files for input variables. A master default-value file sets default values for a number of model parameters, and a main control file sets up the high-level inputs that govern the files listing data for RRUs.

4.3 Initialise and run

The VFM initially examines the domain and RRU data. Then the required combinations of data are assembled and input parameter files prepared for each RRU – in the same way as the recharge models run as stand-alone programs. The VFM assembles the combinations of RRUs and determines and discards the combinations that do not occur within the model domain. For each period the conditions are reassessed and if the land use, climate or soil profile has changed, then a new distribution of pre-RRUs and RRUs is performed before the next set of recharge calculations. As it runs, the VFM may need to create new RRUs if conditions change later in a simulation. The VFM also manages the choice of recharge model and input data for each stress period.

For each RRU, recharge is determined on a daily basis and totalled. The total recharge is then passed to MODFLOW for its time-step calculation. At the end of this time, the new depths to watertable for each cell are passed back to the VFM. The VFM then determines if any RRU's need to change before moving on to calculate recharge for the next stress period.

5 Data collection

A primary constraint on the model's use is the availability of data. Data have been assembled and gaps identified, which have led to recommendations on the collection of further data to complete the record. All datasets and algorithms have been documented and characterised with respect to the level of uncertainty within the data supplied. The data sets and methods of compilation are summarised in Table 1. The procedure followed in preparation of these datasets, with operational definitions relevant to the VFM model that apply to a number of RRUs, are documented in Canci et al. (2003), Aryal and Bates (2001) and Xu and Silberstein (2004).

Data sets assembled for the pilot area are:

- climate spatial distribution
- land-use spatial distribution
- spatial distribution of leaf area index (LAI) of pine plantations and native bushland
- soil classification with profile layering
- soil hydraulic properties – saturated hydraulic conductivity and soil-moisture retention functions (K-ψ-θ) for each soil layer
- vegetation water-use parameters and root-zone depth.

For all the datasets identified, operational definitions of the datasets are provided, along with algorithms for processing raw data into datasets and documentation of the datasets' formatting requirements for the WAVES-based VFM.

5.1 Climate classification

Climatic classification of the Perth region (30.5°–32.6°S; 115.0°–116.2°E; 23 000 km^2) was undertaken to provide a basis for delineating zones of different plant water requirements for groundwater modelling. It was found the area has two distinct climatic zones: dry hot climate and subtropical Mediterranean climate. The area was further classified into six climatic subzones based on climatic indices derived from monthly rainfall, pan evaporation and temperature data (Figure 2; see Aryal & Bates 2001). The data used to drive the simulations in these zones are taken from the Bureau of Meteorology's Point Patched Dataset from its SILO database <www.bom.gov.au/silo> for the stations shown in Table 2.

Table 1 Data collection for the vertical flux model

Baseline data	Method	Data product
Topography	Use the high-resolution elevation contour map	1 m contour map in GIS format
Soil map and profiles	Topsoil data from DAFWA Subsoil – geological map from DoW	Soil map met modelling requirement in GIS map
Groundwater level	Generate level contour from monitoring data	Hydraulic head contour map
Land use		Data in GIS format
urban rural wetland vegetation	Obtain data files from various sources (Landgate, MfP DAFWA etc.) Validate these data Prepare data in suitable GIS format	Current land-use data Vegetation density from 1985 onward in 2-year interval.
Water use		Data in GIS format
ex-house	Obtain data from domestic water use study	Water allocation database (DoW), garden bore distribution, WC abstraction data back to 1980
private bores	Private bores' water demand from DoW	
others	Local council for park irrigation	
Septic tank	Infill program	
Rainfall-pattern modelling	Obtain data from BoM Analysis of spatial distribution of rainfall Develop numerical model to generate daily rainfall for the VFM	Stations to be used Spatial distribution of rainfall Numerical model not required as sufficient data exists for current domain
Other recharge models (market gardens, wetlands, urban)	Collect data from DAFWA Analysis of data available	Market garden and urban water-use pattern, potential evaporation for wetlands
Soil hydraulic properties	Use data from literature to fill the data gaps (CSIRO, DAFWA, UWA) Measure soil-moisture characteristics and K_{sat} as required (UWA and CSIRO)	Soil-moisture characteristic tables for each recharge unit
Meteorological data	Obtain from appropriate agents	Climate data (Aryal & Bates, 2001)
Vegetation parameters	Collect typical data for major vegetation (see WAVES manual) Use remote sensing to derive LAI, with determined calibration	Typical parameters for major vegetation Specification to infer LAI from remote sensing Historical LAI data
Classification of RRUs	Apply GIS techniques to classify the recharge response units based on soil, land use, vegetation, climate, depth to watertable	Method for classification Mechanism to apply the method in dynamic VFM MODFLOW link

Table 2 Climate stations used for simulations within the domain

Zone	Station name	Latitude (°S)	Longitude (°E)	Average rainfall (mm)	Annual potential evaporation (mm)
1	Berkshire	30.54	116.13	414	2170
2	Chelsea	30.63	115.78	485	2125
3	Lancelin	31.02	115.33	638	2060
4	Perth airport	31.93	115.98	750	2050
5	Perth regional office	31.95	115.87	803	1760
6	Jarrahdale	32.33	116.05	1080	1665

5.2 Land use and leaf area index

Canci et al. (2003) describes spatial determination of land use and LAI from satellite data. Figure 3 shows land use (as at 1995) from this process. LAI is a measure of leaf density: a value of 2 means there are 2 m^2 of leaf surface for each square metre of ground surface (units are m^2/m^2, that is, dimensionless). Maps of LAI determined from Landsat (figures 4 and 5) were generated for each available year and used to specify the forest density across the region with time. Figures 4 and 5 show the temporal sequence of LAI for the two most significant vegetation types in the pilot area: pine plantations and native bushland.

LAI determination from the Landsat image is based on a calibration against the normalised difference vegetation index (NDVI), adjusted as described by Hodgson et al. (2003). Figure 6 shows the relationship between measured LAI on the ground and the Landsat NDVI on which figures 4 and 5 are based. Clearly the relationship for the pine plantations is very good, while the relationship for the native bushland is much less so. As discussed in the conclusions of this report, work is underway to collect further data on the native bushland LAI to establish the reliability of Landsat measurements for this purpose. In particular, the work undertaken to date does not include reliable estimates of the native understorey because of the labour-intensive field requirements.

The data given for banksia woodland in Figure 6 are only for sites where LAI was estimated to be dominated by overstorey. This is to limit the influence that the poorer estimate of understorey would have on the relationship. Model testing has progressed to the stage where this now limits our ability to further test the model and it is proposed to fill this data gap in the near future.

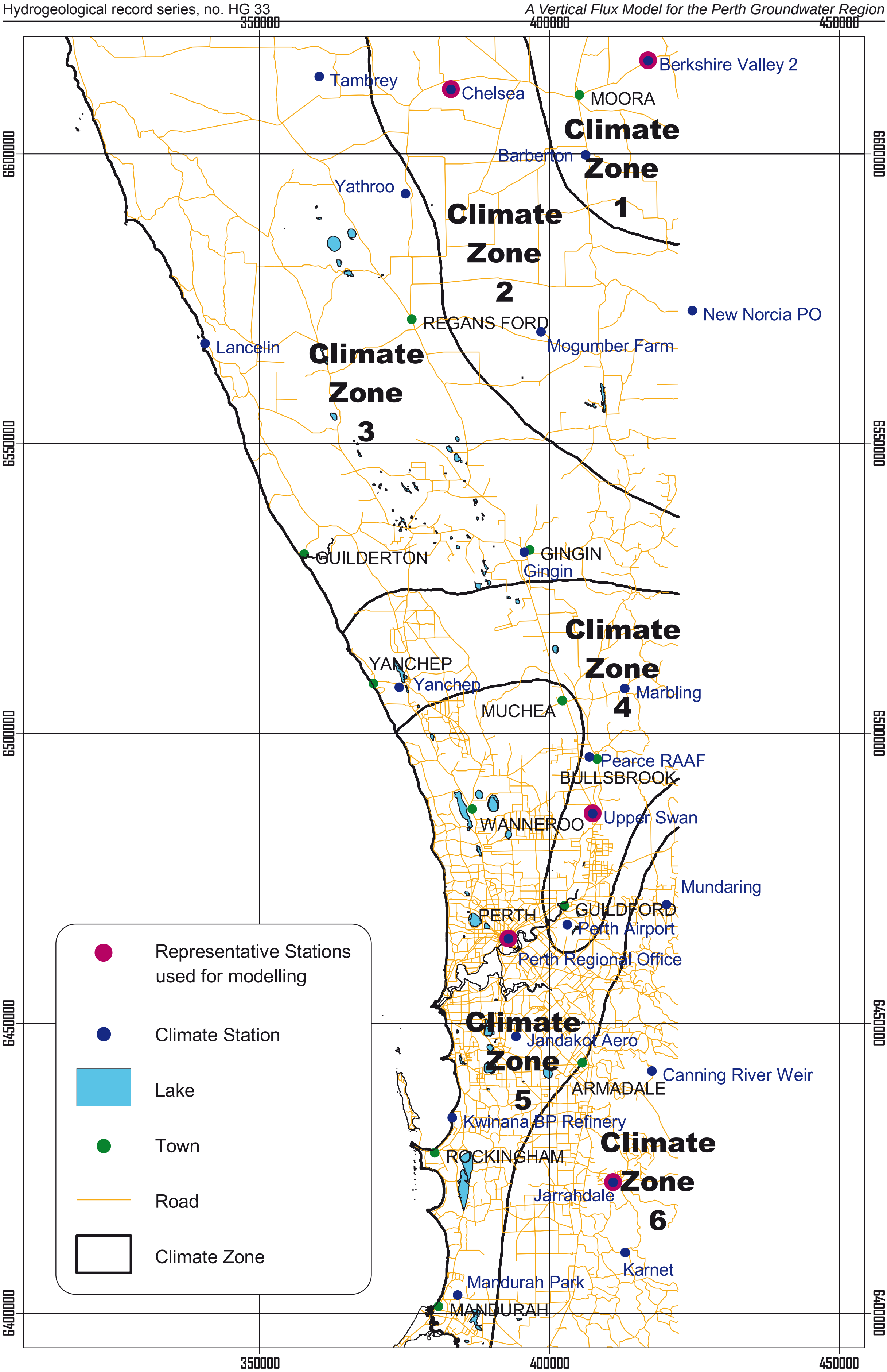

Figure 2 Climatic classification of the model domain

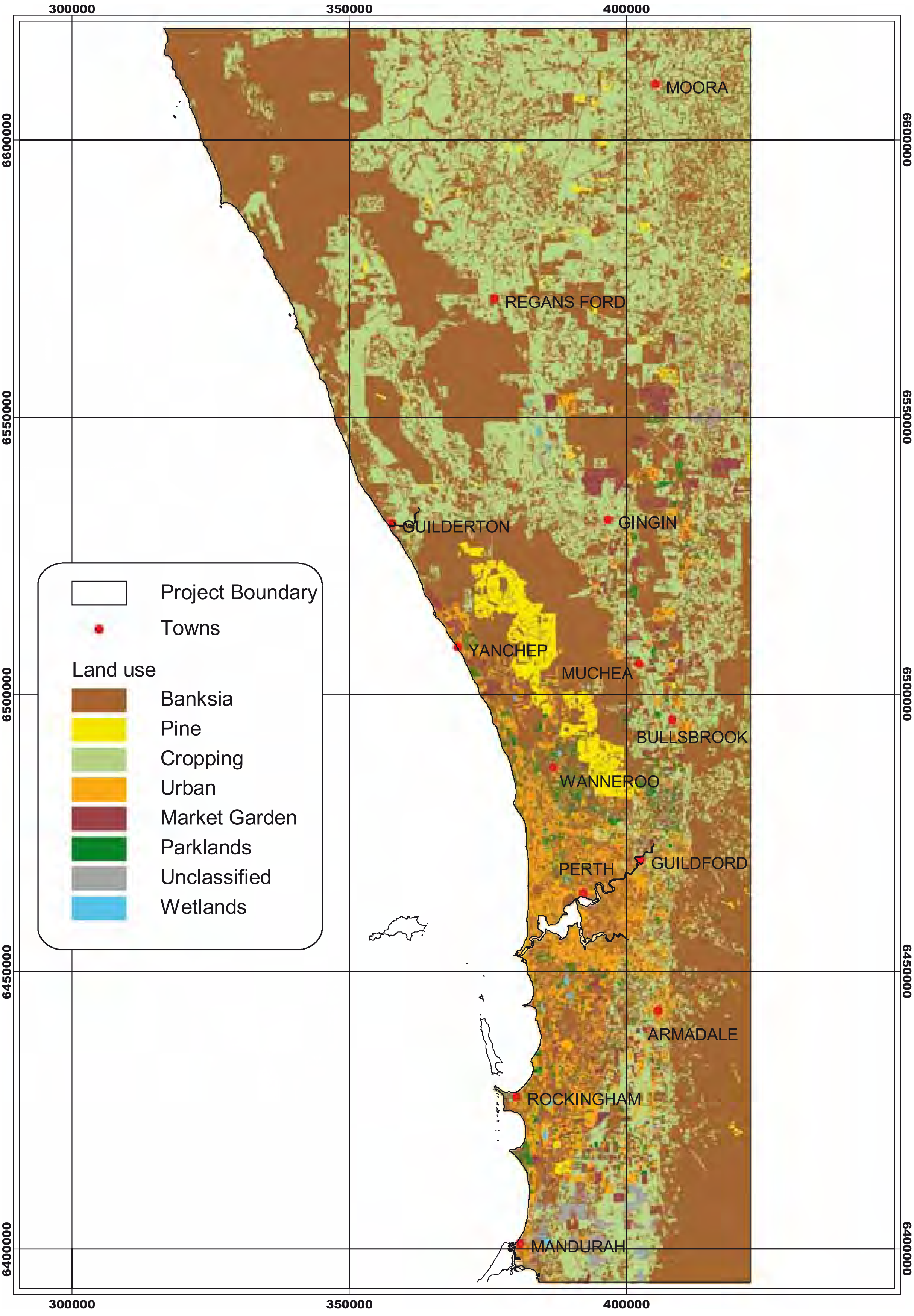

Figure 3 Land use map in 1995

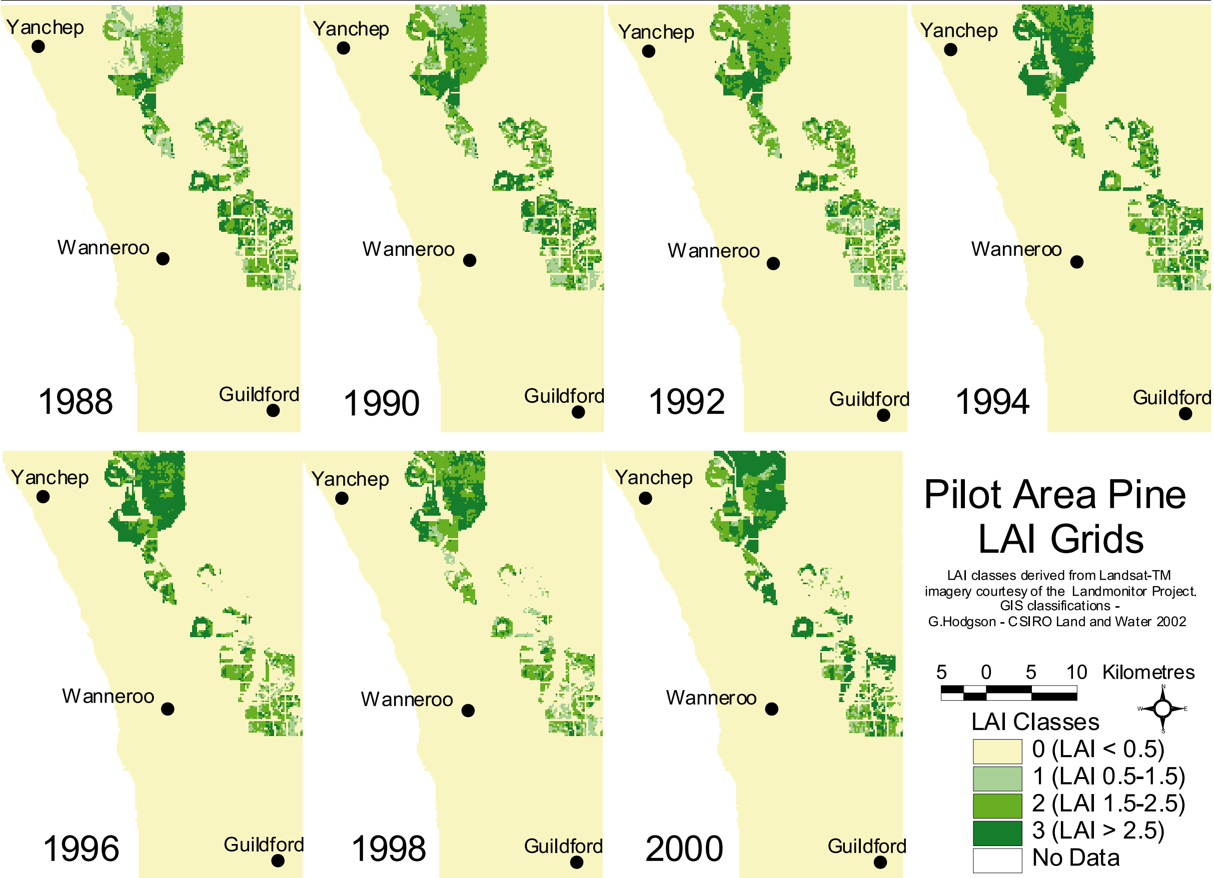

Figure 4 Temporal sequence of LAI of pine plantations in the pilot area

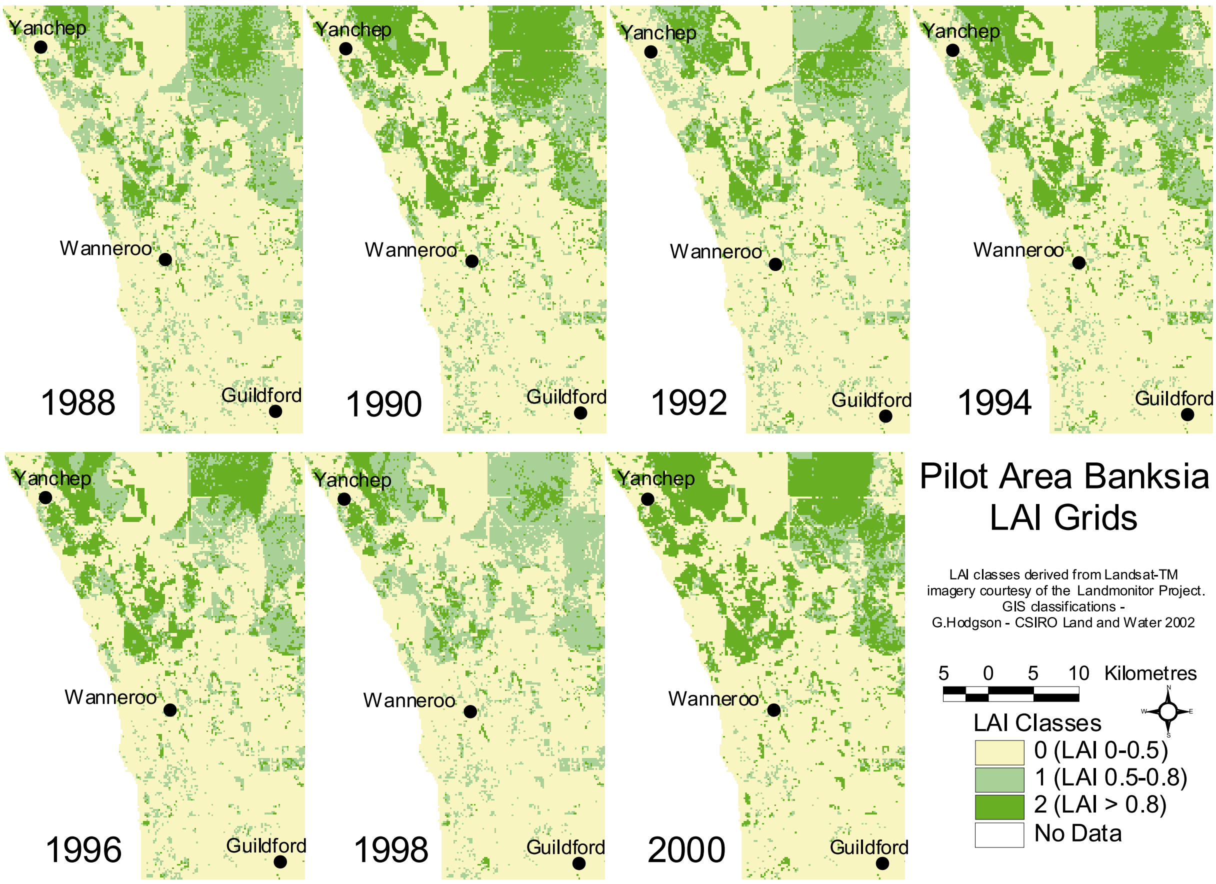

Figure 5 Temporal sequence of LAI of native bushland in the pilot area

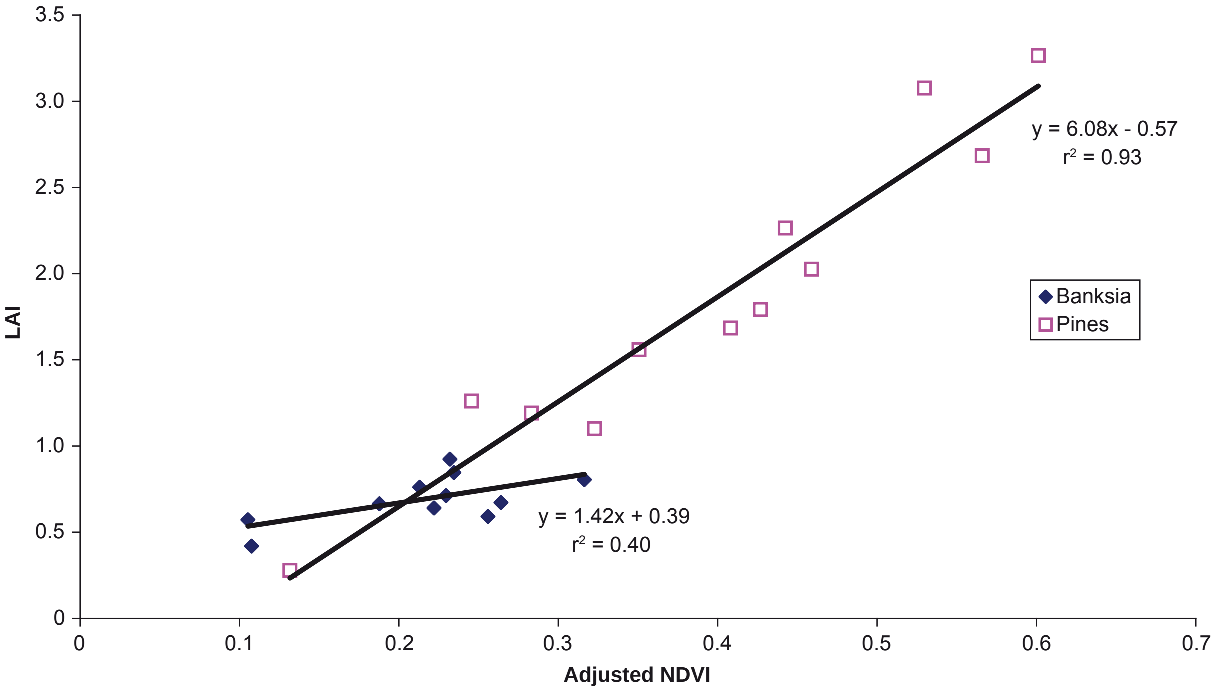

Figure 6 Relationship between ground LAI measurements and Landsat 'adjusted' NDVI (Hodgson et al. 2003) for pine plantations and native banksia woodland

5.3 Soil classification

Spatial soil classification (Figure 7) originally used the methodology given by Wells (Land Assessment P/L 2001), although it was found that many of that document's soil hydraulic parameters did not correlate well with other measurements. It was concluded that this was largely related to the averaging process in coalescing the soil classes into the necessary large-scale classifications. In addition, Wells' classification was based on the Department of Agriculture and Food (DAFWA) database on topsoil to about 1 m depth. To get a better soil-profile classification and incorporate the available geological information, the surface geology generated by Davidson and Yu (2004) was used as the base – resulting in six soil-profile classes (Canci et al. 2003). For each soil profile, soil layers were developed from data on soil lithology. Hydraulic properties for each soil type were characterised using data from CSIRO, the University of Western Australia and DAFWA (Xu 2003). In particular, soil-moisture retention measurements by Smettem (2002) were used to characterise the sandy-loam layers, and similar measurements by Vermooten (2002) were used for the subsoil in the Bassendean and Spearwood soil associations. Topsoil characteristics were determined from measurements by Salama et al. (1999), as described in the Phase I report. These have been supplemented by data from K. Smettem (personal communication 2003) collected as part of this project.

Because the model solves Richards' (1931) equation, an accurate description of the soil layering is required. In many cases this can be approximated for our purposes by a two-layer surface soil and a single subsoil, provided the hydraulic conductivity

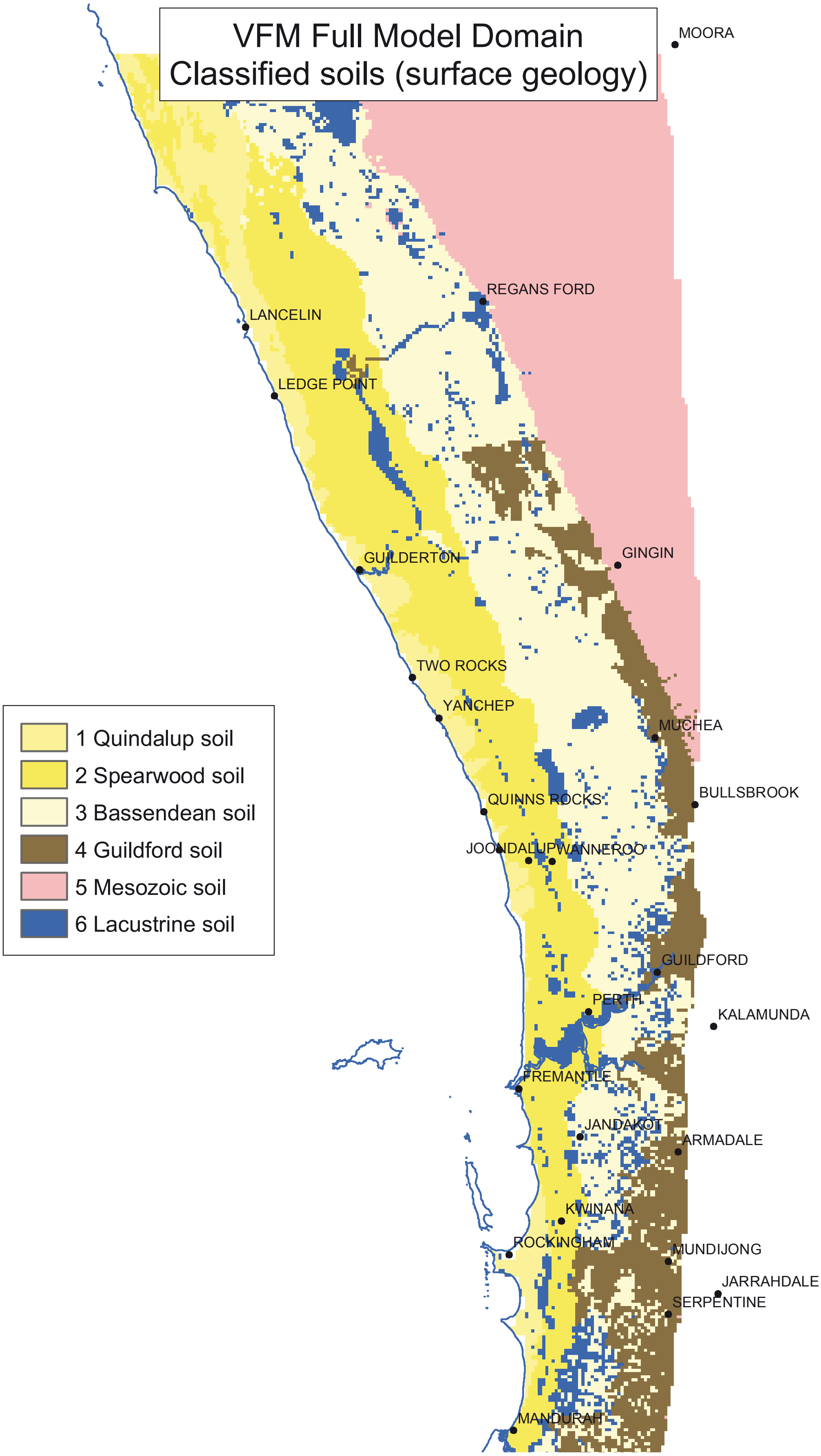

Figure 7 Soil classification of the region

of the simulated profile is close to the harmonic mean for the actual profile. It is significant that the water's rate of passage through the soil profile, and its retention within the root zone, is highly dependent on the soil-moisture characteristic; thus having an impact on the calculation of recharge (in both quantity and timing).

The model requires look-up tables for all soil classes. These are generated by a computer program – SoilPC® CSIRO Land and Water – supplied with the model. A number of soil-moisture retention models may be used, but the preferred model for the soils in the domain is the Campbell model, modified by P. Ross (as used in the SWIM model) (Campbell 1985; Ross & Bristow 1990). Model parameters for each soil type are given in Table 3.

Table 3 Soil characteristic parameters and fitted Campbell model parameters used

Soil layer	**Depth** (m)	K_{sat} (m/d)	θ_{s*}	**b**	Ψ_e (m)	**Estimated soil water holding capacity** (%)
			Quindalup soil profile			
A	0–0.15	5.5	0.33	1.0	-0.15	4
B	0.5–50	15.0	0.33	0.9	-0.12	3
			Spearwood soil profile			
A	0–0.15	3.41	0.37	1.2	-0.10	6
B	0.15–0.5	3.64	0.36	0.9	-0.12	3.5
C	0.5–50	10.00	0.33	0.9	-0.12	4
			Bassendean soil profile			
A	0–0.15	1.63	0.38	0.9	-0.12	3.5
B	0.15–0.5	3.59	0.35	0.8	-0.15	3
C	0.5–50	15.00	0.33	0.9	-0.12	3
			Guildford soil profile			
A	0–1	0.65	0.32	1.5	-0.25	12.5
B	1–30	0.50	0.29	1.5	-0.25	11
			Mesozoic soil profile			
A	0–4	1.0	0.35	1.2	-0.15	7
B	4–30	5.0	0.30	1.2	-0.15	6
			Lacustrine soil profile			
A	0–3	0.05	0.32	2.0	-0.3	17
B	3–30	5.0	0.30	1.2	-0.15	6

K_{sat} = saturated hydraulic conductivity; θ_{s*} = effective saturated moisture content (θ_s -θ_r);
b = Campbell's shape parameter; Ψ_e = the pressure potential at air entry.

5.4 Vegetation parameters for WAVES

The transpiration and evaporation calculations require a number of parameters to characterise the vegetation (Table 4). These parameters essentially control the vegetation's response to environmental conditions and the efficiency of conversion of available energy into evaporation. Measurement of many of the parameters is difficult, and most have not been measured directly within the model domain. However, a body of literature is available documenting the relationships needed to establish parameters for the model.

Table 4 Energy balance and vegetation physiological parameters used in the VFM simulations, with suggested ranges from the WAVES manual (Dawes et al. 1998)

Parameter	Unit	Winter annual pasture		
		Used	High	Low
1 – albedo of the canopy	–	0.85	0.90	0.8
1 – albedo of the soil	–	0.7	0.90	0.65
Rainfall interception	$m\ d^{-1}\ LAI^{-1}$	0.0005	0.001	0.0001
Light extinction coefficient	–	-0.65	-0.7	-0.5
Max carbon simulation rate	$kg\ C\ m^{-2} d^{-1}$	0.025	0.04	0.01
Slope conductance – VPD curve	–	0.9	1.0	0.8
Min available soil water potential	m	-150	-200	-100
IRM weighting of water	–	2	2.5	1.5
IRM weighting of nutrients	–	0.5	1.0	0.2
Stomatal to mesophyll cond.	–	0.2	0.2	0.2
Half optimum temperature	°C	10	12	5
Optimum temperature	°C	20	15	10
Year day of germination[a]	d	-1	100	150
Degree-day hours growth[a]	°C hr	16000	12000	20000
Saturation light intensity	$\mu moles\ m^{-2}\ d^{-1}$	1000	1500	800
Maximum rooting depth[b]	m	1	1.5	0.5
Specific leaf area	$LAI\ kg\ C^{-1}$	24	30	20
Leaf respiration coefficient[a]	$kg\ C\ kg\ C^{-1}$	0.001	0.002	0.0005
Stem respiration coefficient[a]	$kg\ C\ kg\ C^{-1}$	-1	-1	-1
Root respiration coefficient[a]	$kg\ C\ kg\ C^{-1}$	0.0002	0.0005	0.0001
Leaf mortality rate[a]	$fraction\ C\ d^{-1}$	0.001	0.01	0.0001
Above-ground partitioning[a]	–	0.4	0.6	0.3
Salt sensitivity factor[a]	–	1	10.0	0.5
Aerodynamic resistance	$s\ d^{-1}$	30	40	20
Crop harvest index[a]	–	0	0.00	0.00
Crop harvest factor[a]		0	0.00	0.00

Table 4 (continued) Energy balance and vegetation physiological parameters used in the VFM simulations, with suggested ranges from the WAVES manual (Dawes et al. 1998)

Parameter	Unit	Pine			Banksia bush		
		Used	High	Low	Used	High	Low
1 - albedo of the canopy	–	0.9	0.95	0.85	0.8	0.85	0.75
1 - albedo of the soil	–	0.7	0.90	0.65	0.7	0.90	0.65
Rainfall interception	$m\ d^{-1}\ LAI^{-1}$	0.0007	0.002	0.0005	0.0007	0.001	0.0001
Light extinction coefficient	–	-0.45	-0.50	-0.40	-0.45	-0.50	-0.40
Max carbon simulation rate	$kg\ C\ m^{-2}d^{-1}$	0.02	0.03	0.01	0.022	0.03	0.01
Slope of the conductance	–	0.9	1.0	0.80	0.9	1.0	0.80
Max available soil potential	m	-200	-400	-150	-300	-400	-150
IRM weighting of water	–	2.1	2.5	1.0	2.1	2.5	1.0
IRM weighting of nutrients	–	0.3	0.5	0.2	0.3	0.5	0.2
Ratio of stomatal to mesophyll conductance	–	0.2	0.2	0.2	0.2	0.2	0.2
Half optimum temperature	°C	15	20	10	13	20	10
Optimum temperature	°C	20	25	15	24	25	15
Year day of germination[a]	d	-1	-1	-1	-1	-1	-1
Degree-day hours growth[a]	°C hr	-1	-1	-1	-1	-1	-1
Saturation light intensity	$\mu moles\ m^{-2}d^{-1}$	1200	1500	800	1200	1500	800
Maximum rooting depth[b]	m	12	40	10	10	40	10
Specific leaf area	$LAI\ kg\ C^{-1}$	10	10	15	6	10	15
Leaf respiration coefficient[a]	$kg\ C\ kg\ C^{-1}$	0.001	0.0015	0.0005	0.0004	0.0015	0.0005
Stem respiration coefficient[a]	$kg\ C\ kg\ C^{-1}$	0.0006	0.0015	0.0001	0.0006	0.0015	0.0001
Root respiration coefficient[a]	$kg\ C\ kg\ C^{-1}$	0.0001	0.0015	0.0001	0.0001	0.0015	0.0001
Leaf mortality rate[a]	$fraction\ C\ d^{-1}$	0.0001	0.0015	0.0001	0.001	0.0015	0.0001
Above-ground partitioning[1]	–	0.25	0.40	0.20	0.25	0.40	0.20
Salt sensitivity factor[a]	–	1	10.0	0.50	1	10.0	0.50
Aerodynamic resistance	$s\ d^{-1}$	10	20	5	10	20	5
Crop harvest index[a]	–	0	0.00	0.00	0	0.00	0.00
Crop harvest factor[a]	–	0	0.00	0.00	0	0.00	0.00

[a] *indicates parameters with no bearing on model performance in the absence of growth modelling.*
[b] *indicates parameters that varied over the simulations as specified in the simulation descriptions.*

Where possible, parameters have been taken directly from, or estimated from data in, these reports. They are included in the documentation for the model and are added to as new data become available. Finally, some local calibration is required to ensure the parameters are correctly balanced for local conditions, and this was undertaken as part of the sensitivity analysis. Table 4 presents the parameter set used for these simulations.

6 Comparison with field measurements

The modelled and measured recharge has been compared at a number of sites where data are available, but this is surprisingly limited. Explicit measurement of recharge is not possible in most cases, and recharge must be inferred from other measurements and calculated from the water balance by difference.

Figure 8 shows a comparison between the estimates of recharge given by Salama et al. (1999) and the modelled recharge at sites with similar characteristics. A 10-year simulation was performed, from which the results for 1998 were compared with the results from Salama et al. The comparison shows a reasonable agreement, especially given the uncertainties in the site characterisation (Salama et al. 1999 had details only of the topsoils) and the pre-existing land use and soil-moisture conditions. Salama et al. estimated recharge from hydrograph rise and fall analysis, which tends to over-estimate net recharge when the watertable is close to the surface (because some of the water reaching the watertable will be taken up by roots) and under-estimate when the watertable is deep (because the infiltrating wetting front is dispersed and consequently the hydrograph rise and fall is less distinct).

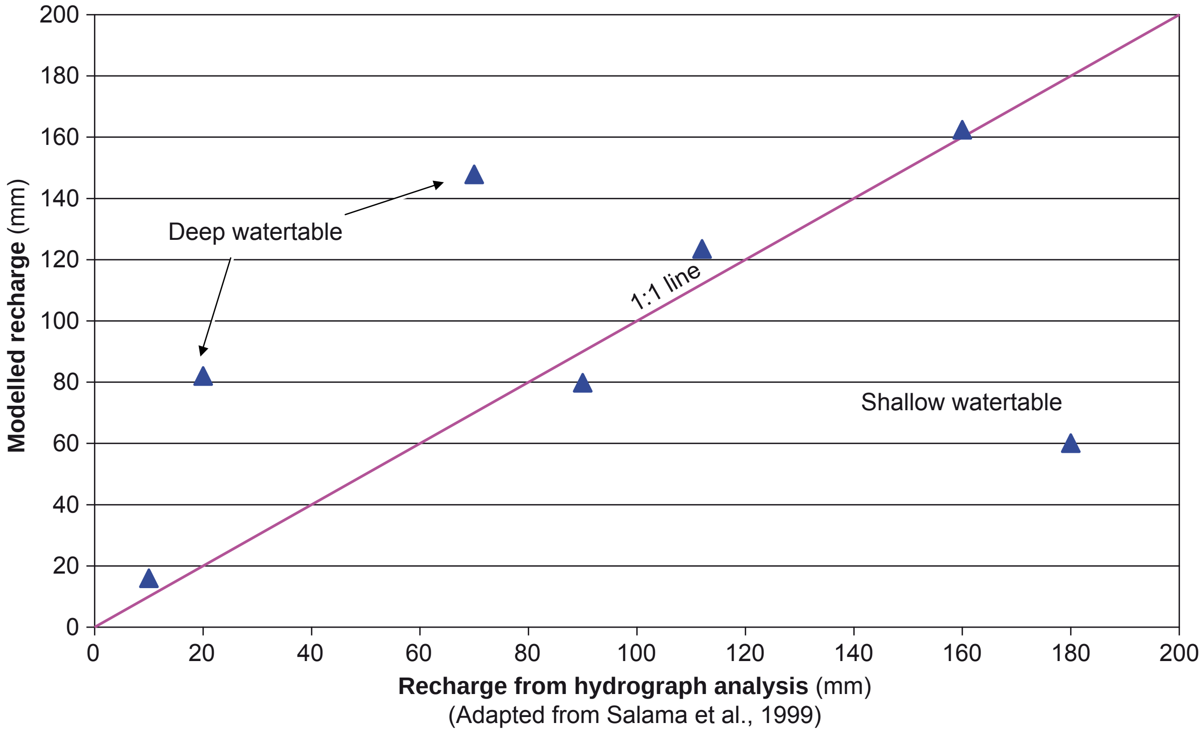

Figure 8 Comparison of recharge as estimated by Salama et al. (1999) and simulations at sites with similar characteristics.

The most complete field study of native-vegetation water use was undertaken by Farrington et al. (1991). Figure 9 shows the study's measurements of evapotranspiration of the understorey (including soil evaporation), overstorey banksia and the two together ('total') plotted against depth to watertable along a transect down a sand dune. While water use for any particular vegetation stratum does not necessarily increase as depth to the watertable falls, total evapotranspiration does. Our modelling suggests that once the watertable falls well beyond the root zone, recharge will stay at a constant level. The depth at which water use is maximised depends on soil and vegetation characteristics.

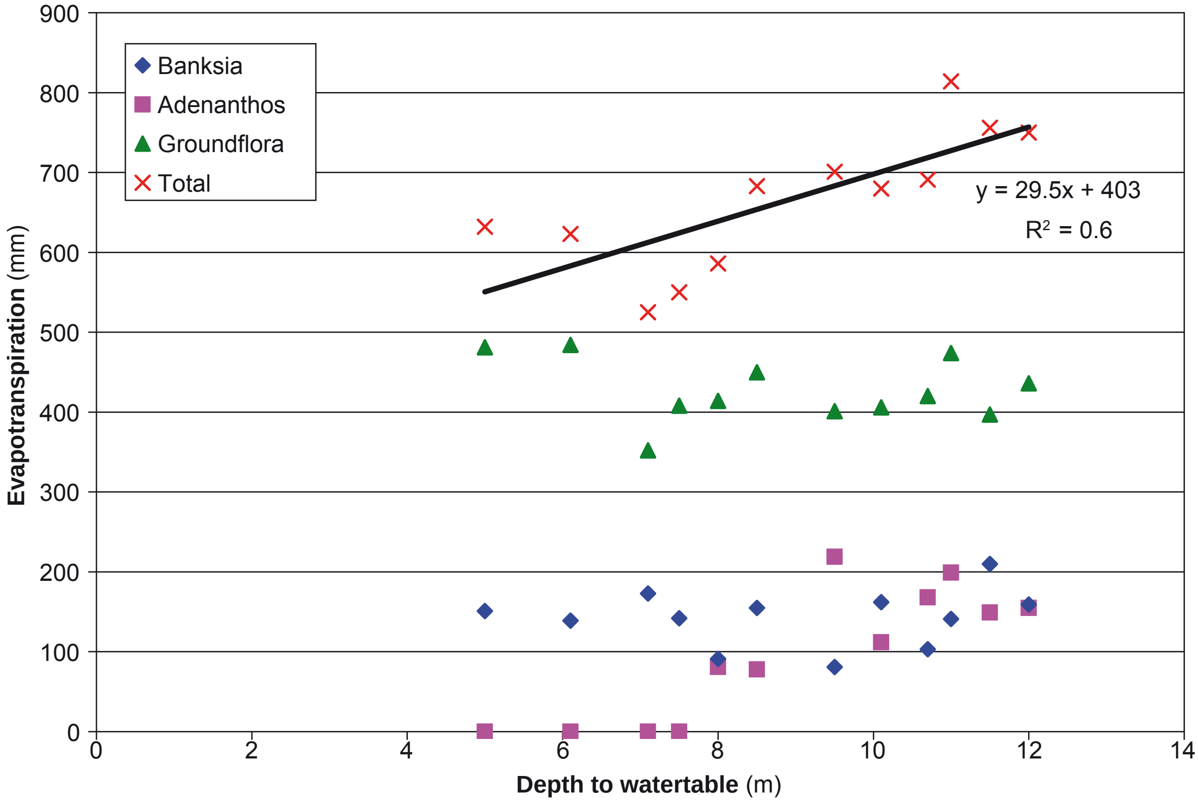

Figure 9 Evapotranspiration plotted against depth to watertable showing ground flora including soil evaporation, mid-storey (Adenanthos) *and overstorey (banksia) (after Farrington et al. 1991).*

There is a well-established relationship between LAI and long-term water use for eucalypts in water-limited environments (Hatton et al. 1998). In the absence of other data, it is assumed that the same holds for the dry sclerophyllous bushland on Gnangara Mound. Figure 10 shows all the LAI data collected at native bushland sites during an associated project (Hodgson et al. 2003) plotted against depth to watertable. The figure shows an increase in LAI as depth to the watertable increases – while it is less than 10 m. This corroborates the data of Farrington et al. and, further, that there appears to be an optimum depth at which vegetation reaches a maximum density (which would consume maximum water). Further work is proposed to collect better and more specific evidence for these behaviours.

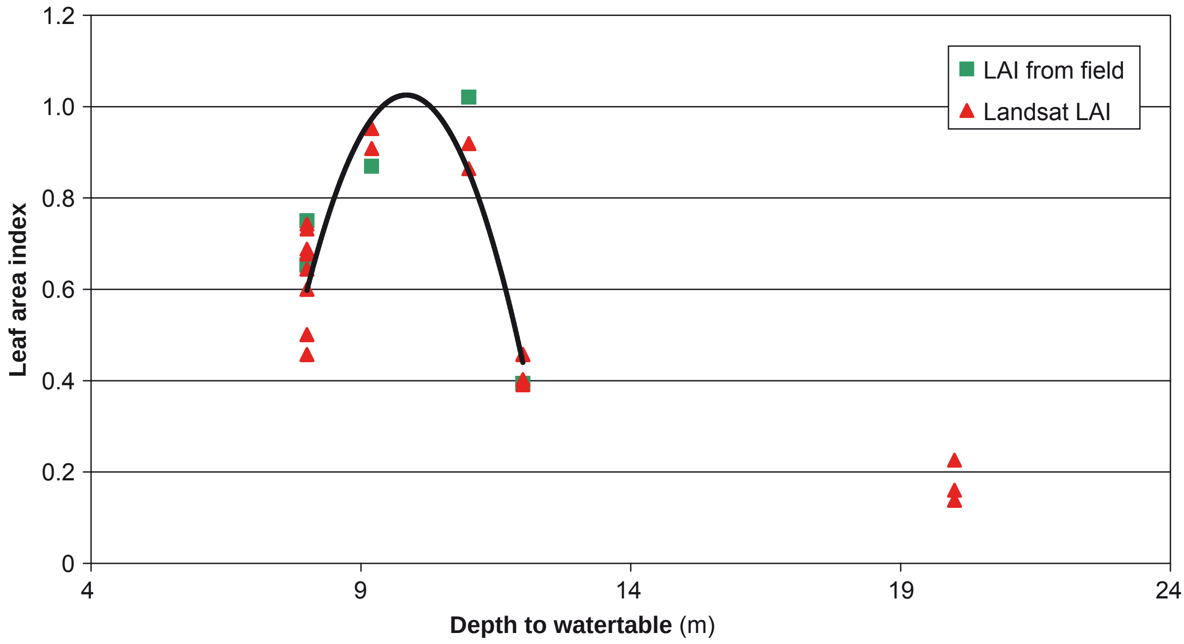

Figure 10 Leaf area index over a range of depths to watertable (LAI data from Hodgson et al. 2003)

6.1 Soil moisture profiles

In May 2002, the Water Corporation installed neutron-moisture-meter access tubes near bores PM4, PM6, PM7, PM9, PV1, PV2 and PV3 (Figure 11). Data from these tubes were used to test the wetting front infiltration in the model, with some results shown in Figure 12.

It is clear from these graphs that the model can simulate the infiltrating wetting front very well. However, it is also clear from this exercise that the use of measured saturated hydraulic conductivity may be fraught with problems as the K_{sat} used here is significantly lower than most of those measured by laboratory methods (Smettem 2002). This illustrates that most of the water is not moving at the saturated rate, and hence the critical parameter to measure is the effective conductivity at field capacity.

6.2 Results from sensitivity analysis

The calibrated model has undergone a comprehensive sensitivity analysis to identify the relative importance of VFM parameters, and to quantify the uncertainty in the model results relative to the uncertainty in the input datasets. Full details of these tests are given elsewhere (Xu et al. 2003).

Table 5 gives the model's simulated recharge for a range of land uses and vegetation densities. The reason depth to watertable does not make a difference under pasture is because once the watertable is beyond the root zone there is no uptake, and all

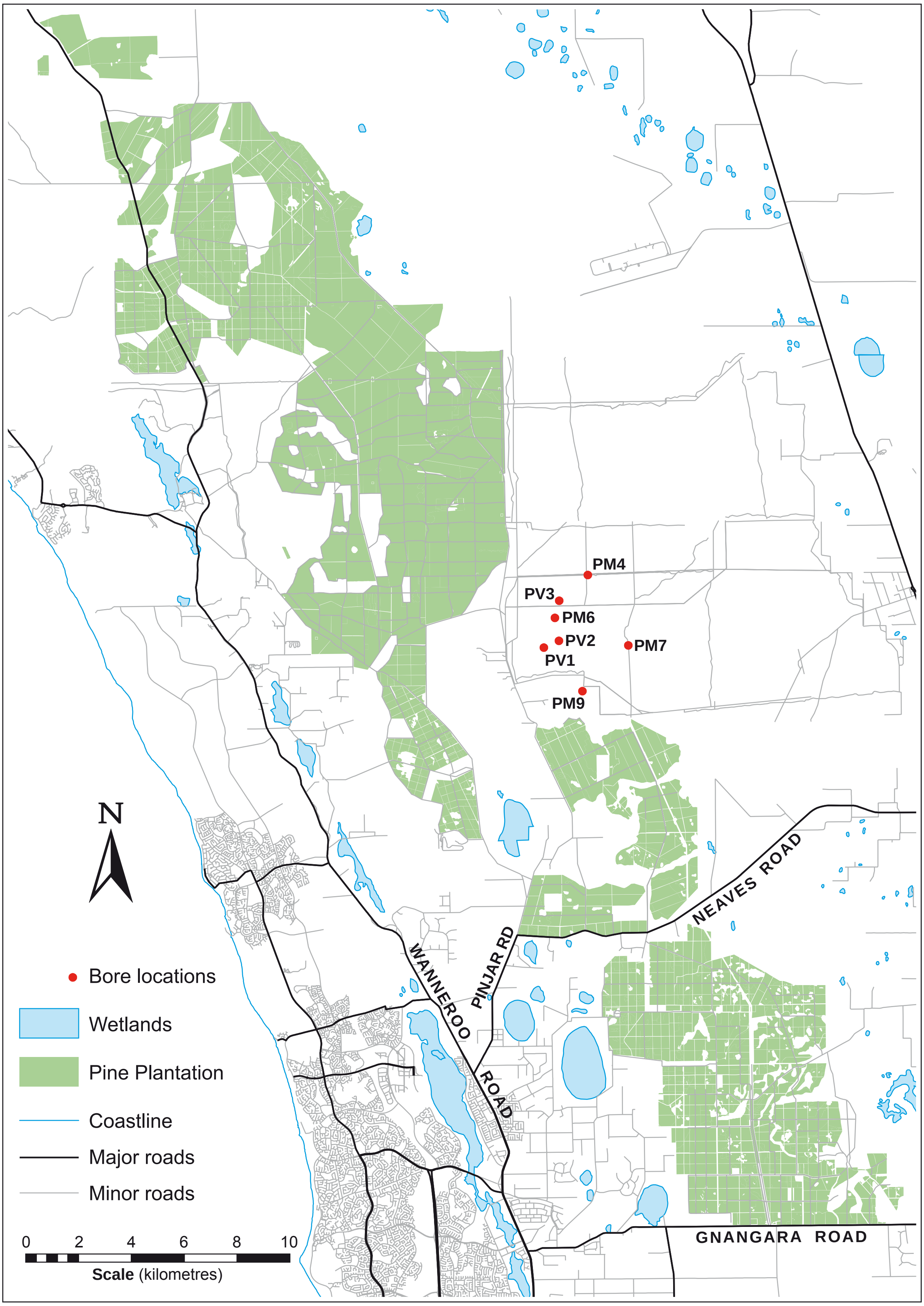

Figure 11 Map showing location of neutron access tube sites used for model comparison with infiltrating wetting front shown in Figure 12

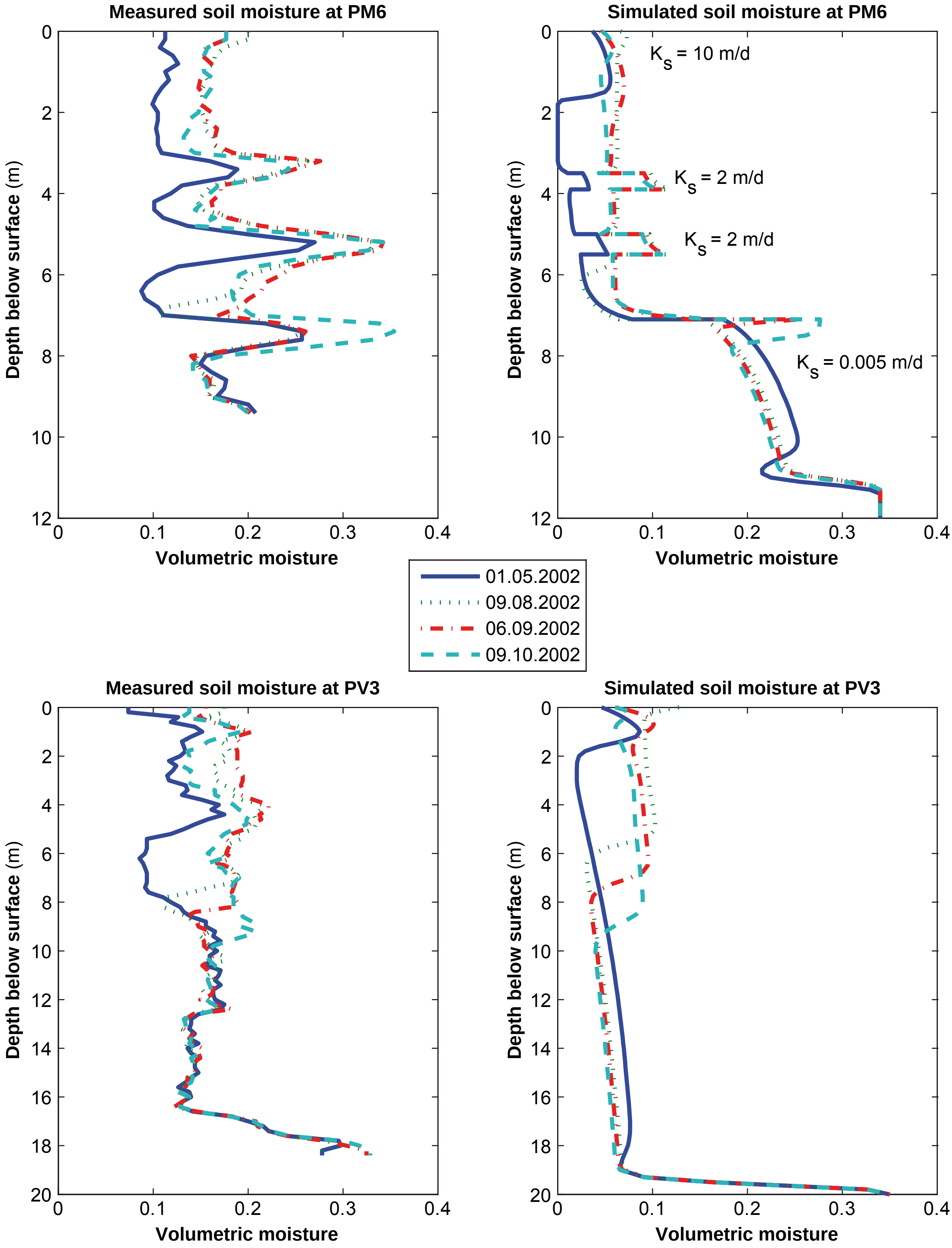

Figure 12 Comparison of neutron access tubes measurements and modelled soil moisture at PM6 and PV3

drainage water eventually reaches the watertable. The results shown are annual averages and so there is no information here about the time taken to reach the watertable. As depth to watertable increases from 6 to 15 m, recharge decreases. This is because as long as the roots can reach further, they have greater opportunity to take up the infiltrating water. It should be noted that these numbers are indicative rather than absolute, because they are dependent on the soil and vegetation characterisation. Water uptake from shallow watertables is easier because the roots do not have to lift it so far. However, if the watertable fluctuates faster than the roots can adapt, they will not be able to make maximum use of it; consequently water use from the watertable will be limited, even though it appears to be within root access. As currently configured in the model, it is possible the vegetation is taking too much water from a shallow watertable. As further data come to hand, these simulations will be modified to reflect the new information.

Table 5 Comparison of average annual recharge (mm) as modelled under different land uses, with different depths to the watertable, taken from a 20 year simulation.

Land use		**Pine plantation**			**Native woodland**		**Annual pasture**
Depth to watertable (m)	**LAI**	3	2	1	1	0.7	0 – 3
		Average annual recharge (mm)					
3		-118	37	263	161	311	373
6		-85	51	245	191	311	373
15		0	15	195	177	301	373

Litter for pines = 1 t/ha, roots of pines truncated 1 m above watertable; litter for banksia = 0.5 t/ha, average annual rainfall = 805 mm; LAI = Leaf area index; Negative indicates that trees extract groundwater.

Rainfall

To evaluate the groundwater recharge response to a wide range of rainfall scenarios, a 20-year dry climate sequence with a mean annual rainfall of 650 mm and a 20-year wet climate sequence with a mean annual rainfall of 900 mm were synthesised by scaling the historical rainfall. These climatic datasets were then used to drive the model simulations. Depths to watertable on the Swan coastal plain vary from zero to over 50 m, but results from only two depths to watertable are presented here: 6 and 15 m being within and just below the natural rooting depth of the banksia. Simulation results indicate a strong relationship between rainfall and recharge (Figure 13).
For a shallow depth (6 m) to watertable, the annual groundwater recharge (GR) correlates strongly with the annual rainfall (R) (GR = 0.801R - 440 with coefficient of determination, $r^2 = 0.92$). The linear function indicates that no net annual groundwater recharge will occur when annual rainfall falls below the x-axis intercept at 550 mm, but rather a net discharge by vegetation uptake. When the watertable is deeper (15 m), the annual recharge has a good correlation with annual rainfall in the high-rainfall regime (GR = 0.587R - 284, with $r^2 = 0.65$). For the low-rainfall regime, it

seems there is no direct relationship between annual rainfall and recharge (GR = -0.216R + 190, with r^2 = 0.28). Close examination of the modelling results, however, revealed that this poor correlation for the low-rainfall regime might be because wet fronts move very slowly through a very dry soil profile, causing significant delay for recharge reaching the watertable. The annual recharge in any particular year may be related to the rainfall in the previous years and hence long-term average recharge is a more appropriate measure of the recharge response to rainfall. Although not shown, when collated into long-term totals, the mean annual recharge is strongly correlated with the mean annual rainfall (GR = 0.858R - 510, with r^2 = 0.999). It should be noted that the above results were obtained with a fixed LAI. Under natural conditions, it is expected that vegetation will respond to water availability by changing the LAI; hence the recharge and rainfall relationship will also change.

Table 6 Recharge as a percentage of rainfall

Annual rainfall (mm)	**Recharge as percentage of rainfall**		
	Watertable at 6 m	Watertable at 15 m	
		Med-High rainfall years	Long-term rainfall
1000	36%	31%	35%
800	25%	24%	22%
700	17%	19%	13%
600	7%	12%	1%

LAI and depth to watertable

Recharge is clearly very sensitive to LAI variation regardless of the depth to watertable (Figure 14), although the magnitude of the effect depends on depth to water. An increase in LAI will reduce the groundwater recharge, because it will result in a higher transpiration rate and an increase in interception by the canopy, thereby reducing the amount of the rainfall available for infiltration into the soil. The sensitivity of recharge to the depth to watertable varies depending on the level of LAI. For low LAI, the recharge is insensitive to the depth to watertable because the rainfall and soil water are sufficient to meet the transpiration demand, and hence vegetation will not use much of the groundwater even when it is very shallow. As LAI increases, the groundwater recharge becomes increasingly sensitive to the depth to watertable, particularly when the depth to watertable is shallow (< 6 m).

Note that several curves show that recharge increases initially as the depth to watertable increases, peaks at a depth that varies with level of vegetation density, and then reduces slightly thereafter. This is consistent with the data presented earlier in the discussion on LAI, total evapotranspiration and depth to watertable.

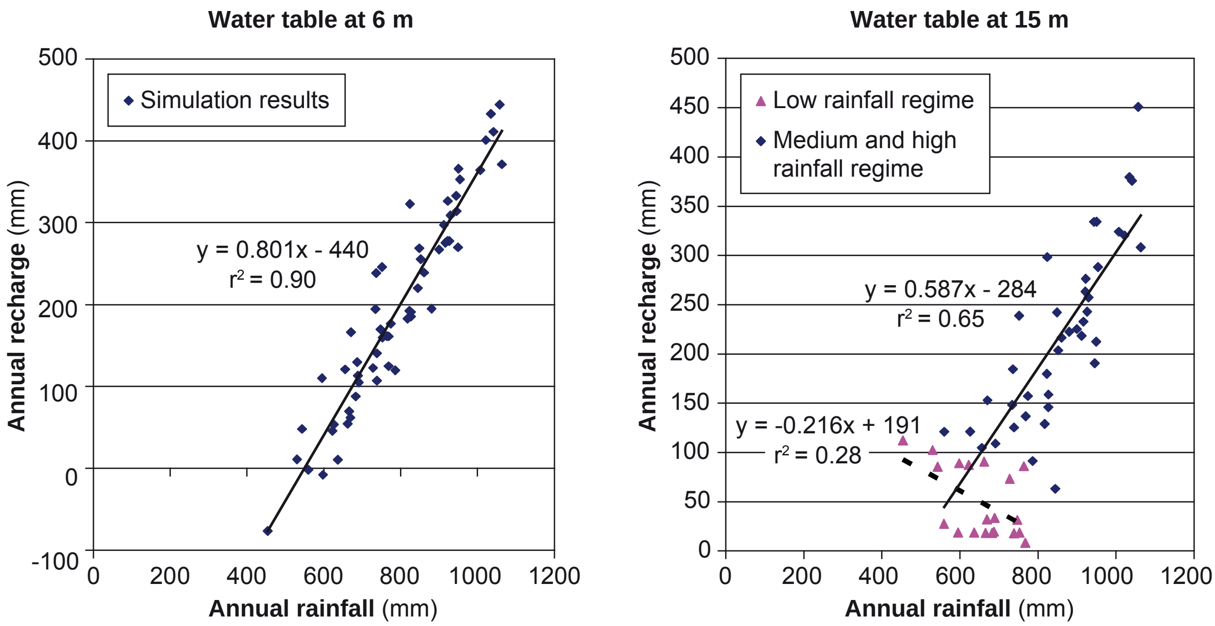

Figure 13 Relationship between annual recharge and rainfall for shallow (6 m) and deep (15 m) watertables

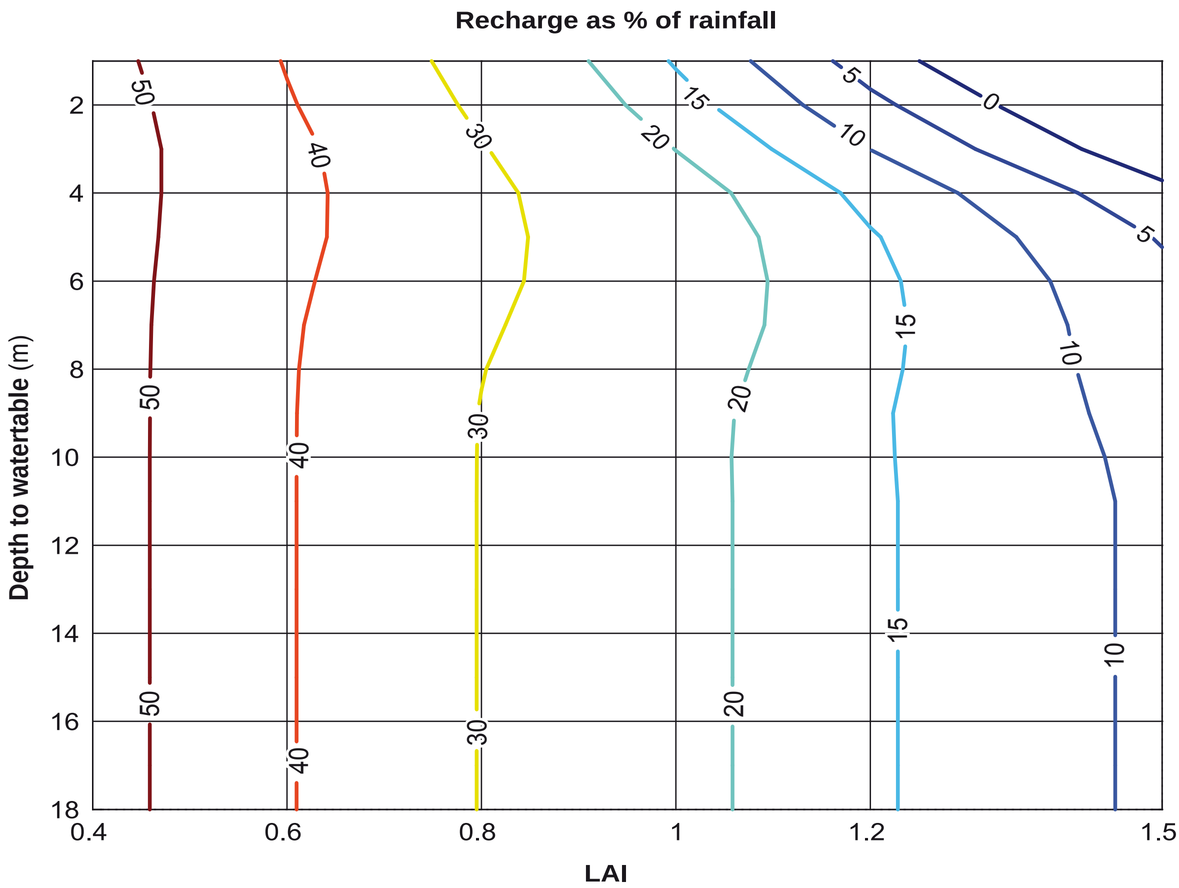

Figure 14 Recharge as a percentage of rainfall vs LAI and depth to watertable for a mean annual rainfall of 805 mm

Soil hydraulic properties

The sensitivity of groundwater recharge to two key soil parameters, the saturated hydraulic conductivity K_{sat} and soil water-holding capacity, were examined. Modelling results indicate that groundwater recharge is relatively insensitive to change in the two topsoil layers. Results are therefore presented for the sensitivity of recharge to the variation of K_{sat} and soil water-holding capacity in the subsoil only.

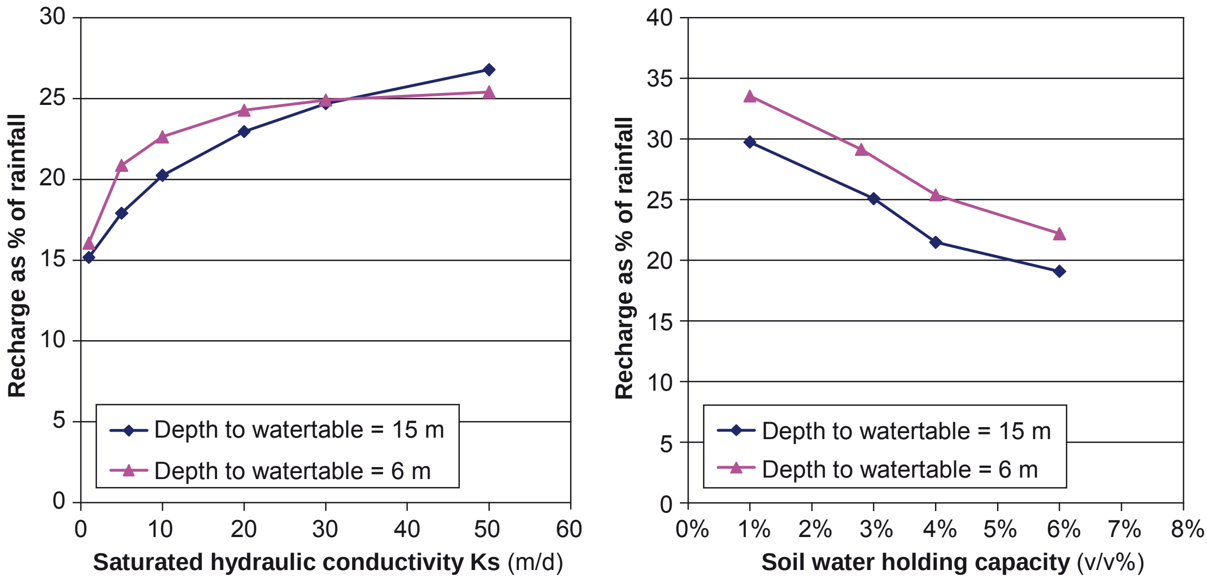

Figure 15 Sensitivity of recharge to variation of saturated hydraulic conductivity (K_{sat}) and to soil water-holding capacity in the subsoil (LAI = 1)

Increasing the saturated hydraulic conductivity (K_{sat}) of the subsoil results in increased groundwater recharge (Figure 15). This is because the more rapid downward movement of the wetting front, as well as drainage of the profile in more permeable soil profiles, reduces the water available for plant uptake. The relationship between recharge and K_{sat} is non-linear, particularly at the low end of K_{sat}, although it tends to linearity and becomes less sensitive to K_{sat} at the higher values. Groundwater recharge reduces gradually as the soil water-holding capacity increases. Increased soil water-holding capacity will increase the amount of rainfall stored in the soil profile during winter, which is subsequently available for vegetation use.

Maximum rooting depth and root distribution

While increasing the rooting depth decreases the amount of groundwater recharge (Figure 16), the relationship between recharge and maximum rooting depth is non-linear – with the effects being more pronounced when maximum rooting depth is less than 12 m. Recharge becomes insensitive to the maximum rooting depth when the rooting depth is over 15 m.

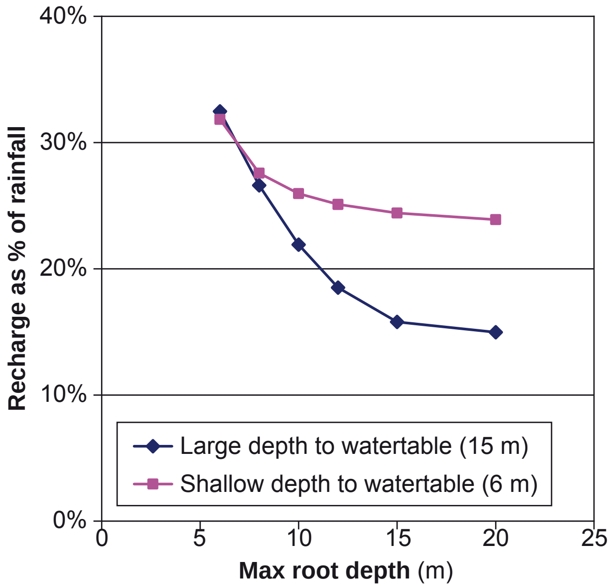

Figure 16 Sensitivity of recharge to maximum root depth and depth to watertable with a constant LAI = 1

Recharge is also moderately sensitive to rooting distribution within the soil profile. Table 7 illustrates the effects on recharge of three rooting patterns that decay linearly, exponentially and logarithmically to a maximum rooting depth of 10 m. Recharge is greatest for an exponential and least for a logarithmic root distribution, with a linear distribution between these two. This is because a rooting pattern with a logarithmic distribution has roots more evenly distributed throughout the soil profile, which enables the vegetation to extract more soil water in the lower part of the soil profile.

Table 7 Effect on recharge of rooting patterns

Depth to watertable (m)	Recharge as % rainfall for different rooting distributions		
	Exponential	Linear	Logarithmic
6	30.8%	27.0%	25.9%
15	27.6%	23.6%	21.9%

Other vegetation parameters

The sensitivity of recharge to the relevant vegetation parameters listed in Table 8 was examined by increasing each parameter by 10 per cent while keeping other parameters constant. Percentage change in recharge compared with the 'reference' recharge value was used to measure the sensitivity. Results are similar under large and shallow depths to watertable, so only results for large depth to watertable are presented in Table 8. To compare the relative sensitivity of model parameters, some of the parameters already discussed are also included here.

The groundwater recharge estimate is relatively insensitive to most of the vegetation parameters, and only those with significant impacts are listed. The most sensitive parameter is LAI, followed by the light extinction coefficient; whereas the impact of litter was very small. Decreasing the light extinction coefficient by 10 per cent will increase the vegetation transpiration, and hence reduce the recharge by a similar percentage. The light extinction coefficient depends on the leaf characteristics and the geometry of radiation scattering with respect to the canopy's architecture, and can be determined by measuring the attenuation of radiation in a plant canopy. Recharge is also sensitive to the maximum rooting depth, maximum carbon assimilation rate, and sensitivity of stomatal conductance to atmospheric vapour pressure deficit. For the soil properties, groundwater recharge is not very sensitive to change in the saturated hydraulic conductivity but is moderately sensitive to the soil water-holding capacity. The information presented in Table 8 can be used to direct efforts on future data collection for further model improvement.

Table 8 Sensitivity of recharge to a list of model parameters

Model parameters	**Value**	**Change by 10%**	**% change in recharge**
Rainfall interception (m day^{-1} LAI^{-1})	0.0007	0.00077	-2.9
Light extinction coefficient	-0.45	-0.495	-12.2
Max carbon assimilation rate (kg(C) $m^{-2}day^{-1}$)	0.022	0.0242	-6.5
Slope of the conductance	0.9	0.99	-6.5
Max rooting depth (m)	10	11	-7.7
LAI (m^2 m^{-2})	1	1.1	-14.2
Litter (kg m^{-2})	0.05	0.055	-0.5
K_{sat} (m day^{-1})	15	16.5	1.6
Soil water-holding capacity (v/v%)	0.03	0.033	-4.1

6.3 MODFLOW-VFM pilot study

The coupled model has been evaluated on a subregion of the Swan coastal plain, in which its ability to simulate water-level response in the superficial aquifer was tested. The Water Corporation developed a MODFLOW model for the south Gnangara Mound area, calibrated in a transient simulation (CyMod 2002). The pilot study showed that the coupled model represented relevant conditions on the Swan coastal plain to an acceptable level. The pilot study also provided a quantitative understanding of the linkage between the VFM and MODFLOW, and the relationship between the aquifer response and recharge from different land uses. Results of the pilot study and the full implementation are reported separately (CyMod 2004; Xu et al. 2004).

7 Conclusions

The model's development is complete. It is now being used for planning and exploration of groundwater and land-management issues on Gnangara Mound. The model's structure allows a wide range of direct biophysical questions to be asked and scenarios explored that were not available in previous models of this system. The sensitivity analysis and comparison with available data have shown the model performs reasonably well in reproducing field measurements. However, these measurements have only been available for a limited range of conditions. The physical structure of the model (which is its essential power) also presents the requirement to provide detailed biophysical parameters, which may be difficult to collect directly. This is being addressed with a range of field exercises funded as associated projects.

Leaf area index (LAI) is the single-most important vegetation parameter for quantifying the water balance, and requires mapping over large areas. The project has developed a good relationship between LAI of the pine plantations and the Landsat measurements. Preliminary work found that the equivalent relationship for the native bushland was much less reliable. Recent work funded under an associated project has greatly improved the relationship between Landsat images and ground measurements of LAI (Hodgson et al. in prep). It is important that the soil hydraulic characteristics are adequately represented for calibration and testing of the vertical flux model (VFM). This is also being addressed in a related project led by Keith Smettem at the University of Western Australia. It is critical that characterising the saturated aquifer is given as much attention as the unsaturated zone and recharge.

It is essential that estimates of the overall water balance of the major land-use systems are quantified or there will be no real test of the model's performance. In particular, recharge needs to be quantified under different land uses, soils and depth to water. Although a number of published records of recharge and evaporation measurements on the Gnangara Mound are available – see Silberstein (2004) for a detailed review – it is impossible to put a complete story together. It is therefore proposed that a series of large-scale experiments to measure water levels, soil moisture and fluxes under each of the major land uses is undertaken. This would result in much-improved validation data for the model and a better estimate of the impact of modifications to existing land uses on the Gnangara Mound. It would permit comparisons of recharge under different land uses, soils and depths to watertable.

8 Recommendations for Future Work

8.1 Effects of alternative land management

It is proposed that a grid of sites including the major land uses (pines, native bushland, market gardens and urban) be established and equipped with loggers. Areas where land-use changes are proposed about two years after installation are recommended, as well as sites where the current activity will continue for some time. After an initial period (two years) a block of each land use will be modified: removed in the case of pines and banksias, or added in the case of urbanisation. For irrigated horticulture, monitoring is proposed for properties with currently unused as well as some used land. These activities would be best undertaken simultaneously, but could be staggered to cover the most critical land uses first – as long as sufficient monitoring data are collected to allow comparisons of the sites.

An intense network of monitoring wells, neutron-moisture-meter access tubes, logged frequency domain soil-moisture probes, and sapflow measurements will facilitate determination of diurnal trends in water use, allowing quantification of daily water uptake.

Water balance of pine plantations over watertables and thinning regimes

There is clearly an imperative to quantify the pine plantations' water use and explore options to manipulate plantation density for optimisation of water and wood production. This has become critical with the LVL plant now operating on the Gnangara plantations. It is apparent from data collected as part of the LAI measurements that opportunities exist to maintain some pine presence at reduced LAI. This would maximise the plantation's water-use efficiency so that both water and wood production can be optimised.

It is recommended that a factorial experiment be undertaken with sites across a range of watertables and plantation densities to quantify the water balance; particularly to what extent pines access groundwater when the watertable is within their root zone. The first phase of this work should be to apply the VFM to simulate water balance data from experiments on the Harvey coast plantations. DEC has an extensive dataset that will be made available for this. A project description has been prepared separately to this report.

Water balance of native vegetation

Recharge cannot be measured in the field; but because the Gnangara Mound has permeable soils, calculation of recharge by the water balance method (rainfall minus evapotranspiration) is likely to give the best possible estimate. An atmospheric flux station measuring evapotranspiration, situated above a site with more than 1 km^2 of continuous common land use, will enable us to close the water balance for that site.

It has been proposed to the National Collaborative Research Infrastructure Strategy/ Terrestrial Ecological Research Network (NCRIS/TERN) that two such flux stations be erected over the native bushland on Gnangara Mound. It is recommended that the Water Corporation fund a part-time technician for three years, and contribute to installation costs for this project.

8.2 Better LAI determination

Better LAI determination for native bushland, wetland vegetation, pine plantations and irrigated horticulture is essential to be confident that the model is operating with realistic input data. Collation of data from published work indicates that LAI increases as depth to watertable increases from 2 m to about 8 m, and thereafter decreases. This has a significant impact on the model's assessment and the potential refinement of the model's water uptake algorithms. It would seem that further data are required to clarify this observation.

The Landsat/LAI relationship needs to be explored in more detail and better estimates of LAI for native bushland should be collected. Data on the relationship of LAI to the basal area of native bushland will enable extrapolation from existing monitored sites to be carried out more easily. This kind of data could be readily collected on existing monitoring sites.

Work to date has treated all native bushland as one entity, with differences in LAI and depth to watertable the only distinguishing attributes. It would be worthwhile determining the water-use similarities and differences between the various vegetation communities. In particular, it is important to better understand the wetland/dryland boundary, both from the existing point of view and as watertables fall.

8.3 Characterisation of root uptake of water and unsaturated soil-moisture fluxes, and improvements to the WAVES model

Root uptake of water from watertables

The root water-uptake algorithm in the WAVES model is a key influence on water uptake and hence on recharge. While the model currently includes state-of-the-art logic for this, the paucity of data makes its application somewhat uncertain. It is important to know how sensitive to depth water-uptake should be. This has a key influence on the impact of falling watertables on native (and exotic) vegetation. It is recommended that a modest increase in the activity associated with an Edith Cowan University project on root water-uptake be undertaken to add valuable and fundamental knowledge in this area.

Effect of falling water levels on native woodland

The impact of receding water levels on phreatophytic vegetation needs to be understood. It is recommended that an experiment is conducted to apply a pulse of infiltrating water over a large-enough area to effectively create a one-dimensional infiltration. Soil-moisture probes should be installed, as well as sapflow meters in trunks inside and outside the wetted area. Water use and water content with depth should be monitored as the wetting front travels down through the soil. In combination with natural isotopes, it would be possible to have measurements of water use in response to a wetting and drying cycle, as well as detailed measurements of the macroscopic rate of water flow through the soil. A drawdown experiment is recommended to understand how the native bushland responds to receding watertables. This could include the pine plantations as well.

Soil hydraulic characterisation

Measurements of saturated hydraulic conductivity are of limited use for the unsaturated zone. By intensively measuring soil moisture and tension during an infiltration event, it would be possible to quantify the unsaturated conductivity. Understanding the limits of K_{sat} measurement with respect to model prediction should help decide the best method for independently determining K_{sat}. It is also important to determine which soil hydraulic model best suits the soil. An infiltration experiment is proposed, which would use continuous logging of soil-moisture content over a period of weeks while a wetting front (generated by an impulse of 100 mm) infiltrated.

Also yet to be established is the significance of the lower hydraulic conductivity (hardpan and clay) layers that exist commonly but discontinuously across the domain at between 6 and 20 m depth. The influence of these layers on vertical flux is not known, or whether perching is significant enough to induce substantial lateral flow.

8.4 Capture and archiving data from earlier studies

A large amount of field data is stored in files and on old computer disks. It is recommended that this be recovered and archived. This would require access to machines that read the old disks that CSIRO no longer owns.

Shortened forms

BOM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEC	Department of Environment and Conservation
DAFWA	Department of Agriculture and Food Western Australia
DoW	Department of Water
EVT	evapotranspiration module in MODFLOW
GIS	geographic information system
LAI	leaf area index
LVL	laminated veneer lumber
NDVI	normalised difference vegetation index
PRAMS	Perth Regional Aquifer Modelling System
PUWBS	Perth Urban Water Balance Study
RRU	representative recharge units
WAWA	Water Authority of Western Australia
MfP	Ministry for Planning
RCH	recharge
SWIM	soil and water integrated model
UWA	University of Western Australia
VFM	vertical flux model
WAVES	Water Atmosphere Vegetation Energy Salt
WC	Water Corporation
WRC	Water and Rivers Commission

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