Mean relative water content in lower soil layer, Jan-Dec 2002
(red: 25th percentile and lower; blue: 75th percentile and higher)

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## Contents

Summary ................................................................................................................................. 3  
1 Introduction .......................................................................................................................... 4  
2 Overview ............................................................................................................................ 5  
3 Progress in AWAP Phase 2 ............................................................................................. 6  
   3.1 Two-layer soil water model .......................................................................................... 6  
   3.2 Prototype operational system and near-real-time weekly products .............................. 6  
   3.3 Historic and climatological runs ............................................................................... 7  
   3.4 Assimilation of Land Surface Temperature .................................................................. 9  
   3.5 Model-Data Fusion ..................................................................................................... 10  
4 Achievements, Outstanding Issues and Next Steps ......................................................... 10  
Acknowledgments .................................................................................................................. 11  
Appendix A: Dynamic Model ............................................................................................. 12  
   State Variables and Balance Equations ......................................................................... 12  
   Phenomenological Equations for Water Fluxes ............................................................... 13  
   Phenomenological Equations for Carbon Fluxes ............................................................ 15  
Appendix B: Observation Model .......................................................................................... 16  
Appendix C: Land Surface Temperature algorithm .............................................................. 18  
Appendix D: Remote Sensing Data Sources ......................................................................... 19  
Appendix E: Operational System ....................................................................................... 22  
Appendix F: Specification of CMAR contribution to AWAP (2006-07) ............................. 24  
Figures ..................................................................................................................................... 27  
References ............................................................................................................................ 37
Summary

The aim of the Australian Water Availability Project (AWAP) is to monitor the state and trend of the terrestrial water balance of the Australian continent, using model-data fusion methods to combine measurements and model predictions. The project (a joint effort by CSIRO Marine and Atmospheric Research (CMAR), the Bureau of Meteorology and the Bureau of Rural Science) determines the past history and present state of soil moisture and all water fluxes contributing to changes in soil moisture (rainfall, transpiration, soil evaporation, surface runoff and deep drainage), across the entire Australian continent at a spatial resolution of 5 km.

The project provides information in three forms: (1) weekly near-real-time reporting, (2) historical monthly time series (1900 to present), and (3) monthly climatologies.

The approach is based on model-data fusion, the combination of information from both data and models to maximise knowledge about the system. Both data assimilation and parameter estimation methods are used.

During the CMAR contribution to AWAP Phase 2 (2006-07), significant progress has occurred in five specific areas: (1) the model; (2) the prototype operational system; (3) historic and climatological runs; (4) assimilation of land surface temperature; and (5) model-data fusion.

At an overall level, there have been two significant achievements to date: (1) the emergence of a mass-consistent, whole-continent, dynamic view of the Australian terrestrial water balance, encompassing both soil water stores and all fluxes influencing terrestrial water (rainfall, transpiration, soil evaporation, surface runoff and deep drainage); and (2) the implementation of this framework in a prototype routine operational system (http://www.eoc.csiro.au/awap/).

There are a number of areas where further development is required, including: (1) dynamic model development to incorporate a comprehensive treatment of plant carbon dynamics, better treatment of different land cover types, and a better treatment of soil evaporation; (2) improvement of the observation model for vegetation greenness; (3) improvement of the observation model for land surface temperature; (4) access to more diverse remotely sensed data streams; (5) access to more timely hydrological data; (6) implementation of the Ensemble Kalman Filter in operational mode; (7) further development of the model-data fusion methodology; (8) possible harmonisation of the data assimilation of vegetation greenness and land surface temperature through a common observation model; (9) writing up the work in scientific papers.

In the medium term (1-2 years), it is envisaged that this prototype operational system for the terrestrial water balance will be linked with similar systems for liquid water balances (eg the Water Resources Observation Network), and that the resulting composite system will transferred to an appropriate operational agency in a way consistent with the National Water Initiative.
1 Introduction

The Australian Water Availability Project (AWAP) is a partnership between the Bureau of Rural Science, CSIRO and the Bureau of Meteorology. To date, the project has involved two phases: Phase 1 took place from January 2005 to June 2006, while the present Phase 2 runs from July 2006 to June 2007.

This is the final report on the CSIRO Marine and Atmospheric Research (CMAR) contribution to AWAP Phase 2, which delivers a prototype operational system (http://www.eoc.csiro.au/awap/). The system constitutes the major deliverable, this report being a supporting document.

The overall objective of AWAP Phase 2 is (AWAP WorkPlan 2006-2007, Version 1.1, as Attachment A to the Collaborative Agreement signed June 2006):

*To develop an operational system for monitoring and predicting soil moisture and other components of the water balance, for spatial scales ranging from 1km to all Australia, and for time scales ranging from weekly to decades.*

The CMAR component of AWAP Phase 2, the subject of this report, has the following specific objectives (see Appendix F for full details):

- **To develop a system to determine the terrestrial water reserve (water in soils and plants) for Australia, combining model and observations using model-data fusion methods.**

- **To apply this system to establish the past climatology and time-evolving present state of the terrestrial water reserve and its controlling fluxes (precipitation, transpiration, soil evaporation, runoff, drainage), at continental scale.**

- **To provide a demonstration system for operational, near-real-time assessment of Australian water availability. This system will deliver near-real-time estimates (including uncertainties) of soil moisture and water fluxes (precipitation, transpiration, soil evaporation, runoff, drainage) with continental coverage, 5 km spatial resolution and weekly time steps, so that estimates are available with a maximum time delay of one week from the end of each weekly assessment period.**

- **To include remotely sensed land surface temperature as an assimilated variable in the model-data fusion system for determining the terrestrial water reserve, on a trial basis over a limited area defined by the Murrumbidgee basin.**

The report is structured as follows. After this introduction, Section 2 provides a short overview of the entire AWAP project. Section 3 summarises the specific progress made in Phase 2 beyond the point reached in the CMAR contribution to AWAP Phase 1 (Raupach et al. 2006). Section 4 summarises overall achievements, outstanding issues and next steps. Most of the detail is relegated to six Appendices, covering (A) the dynamic model, (B) the observation model, (C) the land surface temperature algorithm, (D) remote sensing data sources, (E) the operational system, and (F) specification of the CMAR contribution to AWAP Phase 2.
2 Overview

The aim of the Australian Water Availability Project (AWAP) is to monitor the state and trend of the terrestrial water balance of the Australian continent, using model-data fusion methods to combine measurements and model predictions. The project determines the past history and present state of soil moisture and all water fluxes contributing to changes in soil moisture (rainfall, transpiration, soil evaporation, surface runoff and deep drainage), across the entire Australian continent at a spatial resolution of 5 km. Using the same basic framework, the project provides soil moistures and water fluxes over the Australian continent in three forms: (1) weekly near-real-time reporting, (2) historical monthly time series (1900 to present), and (3) monthly climatologies.

The long-term intention is to contribute to integrated monitoring and understanding of the dynamics of Australian landscape systems, especially responses to climate variability and change, and thus to assist adaptive, system-wide management through feedback via monitoring.

The approach is based on model-data fusion, the combination of information from both data and models to maximise knowledge about the system. Both data assimilation and parameter estimation methods are used. An overview of model-data fusion in this context is given by (Raupach et al. 2006), and more detailed accounts by (Raupach et al. 2005) and (Trudinger et al. 2007a, Trudinger et al. 2007b).

The vehicle for implanting this vision is a model and data assimilation system for the terrestrial biosphere, with a focus on water. Figure 1 shows the seven main components of the system: (1) forcing data, (2) data for assimilation, (3) the model, (4) prior information, (5) the model-data fusion process, (6) a product interface (here the operational system), and (7) mechanisms for product utilisation.

The terrestrial water balance considered in this work applies to water in the (mainly) unsaturated soil column, spatially resolved across the Australian continent. This is defined using two control volumes consisting of "shallow" (typically to depth 0.2 m) and "deep" (typically 0.2 to 1 m) soil layers. Mass balance of water equates the change in the soil water store in each control volume to the sum of the water fluxes across the boundaries of the control volume, so that

\[
\begin{bmatrix}
\text{change in soil water} \\
\text{(layer 1)}
\end{bmatrix} = \begin{bmatrix}
\text{rainfall} \\
\text{transpiration from layer 1} \\
\text{soil evaporation} \\
\text{surface runoff} \\
\text{drainage from layer 1 to layer 2}
\end{bmatrix} - \begin{bmatrix}
\text{change in soil water} \\
\text{(layer 2)}
\end{bmatrix} - \begin{bmatrix}
\text{drainage from layer 1 to layer 2} \\
\text{deep drainage out of layer 2} \\
\text{transpiration from layer 2}
\end{bmatrix}
\]
where input and output fluxes are identified by blue and red colours, respectively. Drainage from layer 1 to layer 2 is an outflow from the upper soil layer and an equal inflow for the lower layer. These equations are written more formally in Appendix A.

Liquid water in aquifers, rivers and reservoirs is not included in the control volumes defined for this work; different control volumes are required to define full water balances for these entities. Some of the outflow fluxes in the above soil water balance equations (such as surface runoff and deep drainage) are inputs to these liquid-water control volumes. If the total Australian water reserve is considered to be the sum of unsaturated soil water ("damp" water) and liquid water in various reservoirs ("wet" water), then this project is focussed on the reserve of "damp" water. In contrast, national water accounting (for instance to support water allocation and trading) is focussed on "wet" water.

3  Progress in AWAP Phase 2

During AWAP Phase 2 (2006-07), significant progress beyond AWAP Phase 1 (Raupach et al. 2006) has occurred in five main areas which together meet all project milestones. This section provides a summary (including keys to milestones). Details are given in Appendices A to F.

3.1  Two-layer soil water model

The single-layer soil water model used in AWAP Phase 1 (Raupach et al. 2006) has been replaced with a two-layer soil water model which predicts water reserves in shallow and deep (typically to depth 1 m) soil layers. These two soil water reserves correspond approximately to short-term (less than a month) and longer-term (seasonal to annual) stores of soil water for maintaining plant growth. The exact depths vary across the Australian continent, being defined by soil maps.

The two-layer soil water scheme has been implemented in WaterDyn, the dynamic model used for water balance prediction in AWAP. Details of the formulation are given in Appendix A. Versions incorporating the two-layer soil water model are WaterDyn12 onward.

For the results described in this report, most spatially varying soil properties in the two-layer soil water model have been set with using continental soil data (McKenzie and Hook 1992; McKenzie et al. 2000). Other (spatially uniform) model parameters have been set to "prior" values using a combination of process knowledge and parameter estimation, from comparisons of model predictions for catchment discharge against data from about 200 "unimpaired" gauged catchments (see Section 3.3).

3.2  Prototype operational system and near-real-time weekly products

Progress reported here meets Milestones AWAP08 and AWAP09 (see Appendix F).

The AWAP prototype operational system (see http://www.eoc.csiro.au/awap/) runs on a weekly basis to provide current estimates of continental soil moisture and water fluxes. Details are given in Appendix E. At present the system runs in forward mode, without step-by-step data
assimilation; instead, off-line parameter estimation has been used to determine prior estimates of spatially invariant model parameters. On-line data assimilation has been tested in pre-operational versions of the model, and will be implemented in the next version of the operational system.

In forward mode, the operational system carries out the following basic steps:

1. Download gridded daily meteorological forcing data (rainfall, solar radiation, maximum and minimum temperature) from the Bureau of Meteorology (BoM). These data are generated operationally by a companion AWAP project.

2. Apply quality assurance checks to BoM meteorological forcing data.

3. Obtain assimilation data as available: satellite imagery of vegetation greenness (AVHRR-NDVI) and surface temperatures (AVHRR), and catchment discharge data from unimpaired, gauged catchments. (In forward mode these data are passed through the model for comparisons with output, but not assimilated).

4. Obtain model initial conditions, from the end of previous run.

5. Set model parameters.

6. Run the WaterDyn model for 1 week, producing daily and weekly-averaged output.


8. Convert model output to Arcview-compatible form suitable for transfer to clients, and to graphical forms suitable for web-based display.

9. Update the web interface.

10. Update archives, logging and run documentation files.

3.3 Historic and climatological runs

Progress reported here meets Milestone AWAP07 (see Appendix F).

The model (WaterDyn18, Australia Run18a) has been used to predict the water balance for the entire Australian continent for 1 January 1955 to 31 December 2006, to provide monthly historic time series and establish a monthly climatology for predicted water fluxes and meteorological forcing variables. The reference period used to define the climatology is 1961 to 1990. The meteorological forcing (rainfall, solar radiation, maximum and minimum temperatures at daily time step, gridded to 0.05 deg spatial resolution) were obtained from the SILO dataset (Jeffrey et al. 2001). Note, however, that Bureau of Meteorology meteorological forcing data are used in the near-real-time weekly runs: see Section 3.2. "Prior" values of spatially uniform parameters were used (Section 3.1).

Figure 2 shows an overview of the historic monthly results in the form of time series over the 26 years 1981-2006, spatially-averaged over the whole continent. The top panel shows the forcing data; the second panel the three model state variables (shallow and deep soil moisture and leaf carbon); the third panel the three fluxes contributing to total evaporation (transpiration from shallow and deep soil layers, and soil evaporation); and the fourth panel the water fluxes from
surface runoff and drainage or leaching. Of these, the leaching flux from the upper to the lower soil layer is an "internal" water flux, not contributing to the net landscape water balance. Local discharge of water is the sum of surface runoff and leaching from the lower soil layer, both assumed to enter river systems and aquifers which are outside the soil control volume used to define the water balance in WaterDyn.

The high interannual variability of the Australian water balance is clear in Figure 2. Runoff and lower-layer soil leaching both vary by a factor of at least four from wet (eg 1983, 1987, 1989, 2000) to dry (eg 1982, 1994, 2002) years. This is much greater than the interannual variability in rainfall and total evaporation, which is less than a factor of two on a continental scale. The reason is that climate variability in rainfall is amplified by a factor of order three in variability in discharge, as is now well known (eg Raupach and Briggs 2005).

As an example of model output in map series form, Figures 3 and 4 show the monthly upper-layer soil moisture over the 26-year period 1981-2006, both as the dimensionless relative soil moisture between 0 and 1 (Figure 3) and as a monthly percentile rank (Figure 4). The monthly percentile rank is the rank of the current month in the cumulative probability distribution for that month over the period 1961-1990, calculated separately at each model point (a 0.05 deg grid cell). Similar map outputs for other quantities are collated in a separate powerpoint file (Australia.Monthly.Run18a.posters.ppt) which forms an addendum to this report and is available on the AWAP website at http://www.eoc.csiro.au/awap/ (under "Documentation").

Noteworthy these map series, evident in Figure 4, are the strong soil moisture deficits in 1982, 1994, 2002 and 2006 (particularly in SE Australia). During the latter part of 2006, an acute soil moisture deficit developed in the lower soil layer which supplies the "maintenance" water reserve for deep-rooted vegetation to survive droughts (see Australia.Monthly.Run18a.posters.ppt). This is due to the ongoing drought from 2001, probably coupled with higher temperatures and other stresses. It is likely to have ecological consequences such as increased mortality in mature native vegetation.

We have tested the performance of WaterDyn (especially the new two-layer soil water model) by comparing predicted and observed discharge for about 200 "unimpaired" gauged catchments across Australia. Catchment outflow data at monthly and daily time resolutions have been consolidated and quality-controlled by Dr Francis Chiew and colleagues, CSIRO Land and Water. Figure 5 shows the unimpaired catchments in SE Australia, which are located mainly in wet areas appropriate for water harvesting. The catchments cover a total of about 1.6% of the Australian land area and represent a highly biased sample of land area with respect to rainfall (the mean precipitation on all unimpaired catchments is over 900 mm/y, compared with a mean of about 465 mm/y for the whole Australian continent). Nevertheless, the discharge data set from unimpaired catchments represents an invaluable resource for model testing.

Figure 6 compares predicted (WaterDyn18) and observed mean discharge for 1981-2006, over all available unimpaired catchments. There is a significant improvement in the quality of this prediction compared with earlier WaterDyn predictions using the one-layer soil water model (Raupach et al. 2006). Further improvements are expected because Figure 6 (like Figures 3 and 4 and other results in Australia.Monthly.Run18a.posters.ppt) was calculated with "prior" parameter
values, which will be improved with step-by-step data assimilation in the next phase of the AWAP project.

3.4 Assimilation of Land Surface Temperature

Progress reported here meets Milestone AWAP06 (see Appendix F).

We have assembled data on Land Surface Temperature (LST) and Brightness Temperature (BT) for the Australian continent, from two sensors: NOAA-AVHRR (as used throughout AWAP) and AATSR (on the EnviSat platform operated by the European Space Agency). Appendix D provides details of sensors and satellite platforms used throughout AWAP. BT is a radiative surface temperature derived without correction for surface emissivity (that is, assuming emissivity = 1), while LST is corrected for surface emissivity and atmospheric effects. The algorithm currently being used to derive LST is given in Appendix C. In addition to BT and LST, our basic data set includes time of satellite overpass, as this is important for the observation model used to relate LST to sensible heat flux and thus (via the surface energy balance) to latent heat flux and evaporation. The observation model used to do this is given in Appendix B.

A snapshot of the data is shown in Figure 7, as LST from AVHRR (NOAA16) and AATSR, on three successive days in summer (3-5 Jan 2004) (upper panel) and two days in winter (16 and 18 Jul 2004). Times are in UTC, approximately 10 hours behind local solar time in eastern Australia. The AVHRR (NOAA16) overpass occurs in mid-afternoon and the AATSR overpass in mid-morning. The much narrower swath of AATSR relative to AVHRR is clearly evident.

All data (BT, LST and overpass time for AVHRR and AATSR) have been resampled and spatially averaged where necessary to produce the standard "data cubes" used in AWAP Phase 2, consisting of daily data through time ("z") on a 0.05 deg spatial grid ("xy") covering the Australian continent.

Our first efforts to model the LST data with the WaterDyn observational model are shown in Figures 8 (AVHRR) and 9 (AATSR). These figures compare observed LST with predictions from the WaterDyn observational model for LST described in Appendix B. The agreement is reasonable, but shows evidence that (1) the model is underestimating observed LST, and (2) the observed LST from AVHRR is warmer than from AATSR. A significant (but not the only) reason for this is the difference in overpass times.

In these initial comparisons, a spatially and temporally uniform aerodynamic conductance ($G_a = 0.05 \text{ m s}^{-1}$) was assumed, although this quantity is actually highly variable in response to surface cover (roughness) and wind speed. Accounting for roughness effects will occur soon.

At this time, the data cubes contain at most one overpass per day. Later, we will explore the use of multiple overpasses per day from AVHRR, to provide additional constraints from resolution of the diurnal cycle of surface temperature (particularly its amplitude). A further remotely sensed data source likely to be important as this idea is pursued is from geostationary meteorological satellites (GMS5, MTSAT-IR), which provide hourly thermal data at 5-km resolution for Australia. These data are currently being acquired by the Bureau of Meteorology.
3.5 Model-Data Fusion

Work on model-data fusion associated with AWAP has led to two published papers (Trudinger et al. 2007b; Trudinger et al. 2007a). These report developments in parameter estimation by sequential model-data fusion methods. This is an important distinction between the approach used here and that used in data assimilation in numerical weather prediction, where the target variables are model state variables rather than parameters.

4 Achievements, Outstanding Issues and Next Steps

Achievements: There have been two significant achievements from this work to date. The first is the emergence of a consistent, whole-continent, dynamic view of the Australian terrestrial water balance, encompassing both soil water stores and all fluxes influencing terrestrial water (rainfall, transpiration, soil evaporation, surface runoff and deep drainage). Consistency is enforced by the use of a water-conserving mass balance. The framework already shows the influence of climate variability on stores and fluxes (eg Figures 3 and 4), and suggests the emergence of trends in Australian terrestrial water availability in response to climate change.

The second achievement is the implementation of this framework in a prototype operational system. The system is designed for routine operation, and is sufficiently modular to allow for straightforward development of individual components.

Outstanding Issues and Next Steps: Although the system is producing results which pass several initial tests (eg the discharge comparison in Figure 6), there are many areas where further development will improve predictions. These include the following.

1. Further development of the dynamic model to include (a) a comprehensive treatment of plant carbon dynamics, (b) better treatment of different land cover types (trees, grass, crops), and (c) a better treatment of soil evaporation.

2. Further development of the observation model for vegetation greenness, making use of the dynamic model developments.

3. Further development of the observation model for land surface temperature, particularly to include a more realistic treatment of aerodynamic conductance and its dependence on vegetation properties (height, cover fraction, structure) and meteorological conditions (wind speed, atmospheric stability).

4. Access to better and more diverse remotely sensed data streams.

5. Access to more timely hydrological data.


7. Further development of the model-data fusion methodology (particularly Ensemble Kalman Filter) to increase the ability of the system to share information among related land cover types.

8. Possible harmonisation of the data assimilation of vegetation greenness and land surface temperature through a common observation model.
9. Writing up the model, data assimilation and operational aspects of the system in appropriate scientific papers, and otherwise fully documenting the model and operational system.

Resolution of these issues is the main tactical task in this work for the coming year.

In addition to the above issues of scientific development, there are three other, more strategic issues:

10. We wish to couple this prototype operational system for the terrestrial water balance with systems for liquid water balances in other control volumes, such as the Water Resources Observation Network.

11. After a development and refinement period for this system in CSIRO, of probably 1-2 years, we envisage that the system will become part of the hydrological monitoring toolkit of an appropriate operational agency in a way consistent with the National Water Initiative.

12. We envisage application of the system developed here to study of the vulnerability of Australian terrestrial water to climate change, by using appropriately perturbed meteorological forcing data as input.

Acknowledgments

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Appendix A: Dynamic Model

This Appendix summarises the equations currently used in the WaterDyn dynamic model for soil water and green-leaf carbon (April 2007, WaterDyn17M).

State Variables and Balance Equations

The model has three state variables, two soil water stores \( (W_1, W_2) \) [mol-water m\(^{-2}\)] and a green-leaf carbon store \( C_L \) [molC m\(^{-2}\)]. Corresponding dimensionless variables are the relative soil water in the two stores \( (w_1, w_2) \) and vegetation cover fraction or green-leaf cover \( v \) (all between 0 and 1). These are respectively related to \( W_1, W_2 \) and \( C_L \) by

\[
w_i = W_i / (\rho_W Z_{Wi}) \quad (i = 1, 2) \tag{1}
\]

\[
v = 1 - \exp(-c_{Ext} \Lambda) = 1 - \exp(-c_{Ext} C_L / C_{L0}) \tag{2}
\]

In Equation (1), \( \rho_W \) is the density of liquid water [mol-water m\(^{-3}\)] and \( Z_{Wi} \) the depth of the extractable soil water [m-liquid-water] in soil layer \( i \) (\( i = 1, 2 \)). In Equation (2), \( c_{Ext} \) is the exponential light extinction coefficient in the canopy, \( \Lambda \) the leaf area index and \( C_{L0} \) the green-leaf carbon store at \( \Lambda = 1 \), given by \( C_{L0} = d_L \rho_{CL} \), where \( d_L \) is the leaf thickness and \( \rho_{CL} \) the density of carbon in green leaf [molC m\(^{-3}\)].

The water and carbon balance equations governing \( W_1, W_2 \) and \( C_L \) are

\[
\frac{dW_1}{dt} = \rho_W Z_{W1} \frac{dw_1}{dt} = F_{WP} - F_{WT1} - F_{WX} - F_{WR} - F_{WD1} \tag{3}
\]

\[
\frac{dW_2}{dt} = \rho_W Z_{W2} \frac{dw_2}{dt} = F_{W1} - F_{WD2} - F_{WT2} \tag{3}
\]

\[
\frac{dC_L}{dt} = a_L \frac{F_{CP}}{NPP} - k_L \frac{C_L}{Leaf \ decay} \tag{4}
\]

In Equation (3), all water fluxes \( (F_W) \) are in metres of water per day [mWater day\(^{-1}\)]. In Equation (4), \( F_{CP} \) is the plant carbon production flux or net primary productivity [molC m\(^{-2}\) day\(^{-1}\)], \( a_L \) the allocation coefficient for growth carbon to leaf, and \( k_L \) the decay rate for leaf carbon [day\(^{-1}\)].

The model uses standard MKS units, but with time in days rather than seconds.
Phenomenological Equations for Water Fluxes

The phenomenological equations governing the water fluxes in Equation (3) are as follows.

(1) Precipitation \((F_{\text{WP}})\) is an external input.

(2) Transpiration \((F_{\text{WT}})\) is defined for each soil layer \((i = 1, 2)\) as the lesser of an energy-limited transpiration rate \(F_{\text{WT}(\text{ELim})i}\) and a water-limited transpiration rate \(F_{\text{WT}(\text{WLim})i}\) :

\[
F_{\text{WT}i} = \min \left( F_{\text{WT}(\text{ELim})i}, F_{\text{WT}(\text{WLim})i} \right)
\]  

(5)

The total energy-limited transpiration rate (summed over two soil layers) is \(F_{\text{WT}(\text{ELim})} = F_{\text{WT}(\text{ELim})1} + F_{\text{WT}(\text{ELim})2}\). This total is partitioned among soil layers using the water-limited transpiration for each layer under prevailing (energy-limited) conditions, so that \(F_{\text{WT}(\text{ELim})i} = F_{\text{WT}(\text{ELim})} \times \left[ F_{\text{WT}(\text{WLim})i} / (F_{\text{WT}(\text{WLim})1} + F_{\text{WT}(\text{WLim})2}) \right]\). Combining with Equation (5), this means that:

\[
F_{\text{WT}i} = \min \left( F_{\text{WT}(\text{ELim})i}, F_{\text{WT}(\text{WLim})i} \right) \frac{F_{\text{WT}(\text{WLim})i}}{\sum F_{\text{WT}(\text{WLim})j}}
\]

(6)

where the sum runs over layers \((i = 1, 2)\). The water-limited transpiration for each layer, \(F_{\text{WT}(\text{WLim})i}\), and the total energy-limited transpiration rate, \(F_{\text{WT}(\text{ELim})}\), are defined as follows.

- The water-limited transpiration rate in layer \(i\) is given by

\[
F_{\text{WT}(\text{WLim})i} = \nu k_{Ei} Z W_i W_i = \nu k_{Ei} \frac{W_i}{\rho_w}
\]

(7)

where \(k_E\) is a rate [day\(^{-1}\)] for the decay of water extraction by roots from a drying soil under water-limited transpiration.

- The total energy-limited transpiration rate is the evaporation rate from surface without water constraints. It is often defined using the Penman-Monteith equation, but for reasons of both physics (Raupach 2001) and simplicity, it is defined here as

\[
F_{\text{WT}(\text{ELim})} = \nu F_{\text{WP}(\text{PT})}
\]

(8)

where \(F_{\text{WP}(\text{PT})}\) is the Priestley-Taylor evaporation rate [mWater day\(^{-1}\)], a thermodynamic estimate of the energy-limited evaporation rate for the whole surface (vegetation plus soil). The factor \(\nu\) (vegetation fraction cover) relates energy-limited total evaporation to the plant component only. From (Raupach 2000) and (Raupach 2001), \(F_{\text{WP}(\text{PT})}\) is

\[
F_{\text{WP}(\text{PT})} = \frac{c_{\text{PT}} \Phi_{\text{Eq}}}{\rho_w \lambda_w}
\]

(9)
where \( \rho_W \) is the density of liquid water \([\text{mol Water} \, \text{m}^{-3}]\), \( \lambda_W \) is the latent heat of vaporisation of water \([\text{J mol-water}^{-1}]\), \( \Phi_{E_0} \) is the thermodynamic equilibrium latent heat flux \([\text{J m}^{-2} \, \text{day}^{-1}]\), and \( c_{PT} \) is the Priestley-Taylor coefficient, a number which is well constrained at about 1.26 (Pristley and Taylor 1972; Raupach 2001). The equilibrium latent heat flux is given by

\[
\Phi_{E_0} = \frac{p_e \Phi_A^*}{p_e + 1}
\]  

(10)

where \( \Phi_A^* \) is the isothermal available energy flux \([\text{J m}^{-2} \, \text{day}^{-1}]\), \( \varepsilon \) is the ratio of latent to sensible heat content of saturated air (2.2 at 20 deg C, roughly doubling with each 13 deg C temperature increase) and \( p \) is a number slightly less than 1 accounting for radiative coupling, defined in the next equation. The isothermal available energy flux \( \Phi_A^* \) is given by

\[
\Phi_A^* = (1-a) \Phi_{S_\downarrow}^* + \varepsilon \left( \Phi_{L_\downarrow}^* - \sigma T_a^4 \right); \quad p = \frac{G_a}{G_a + G_r} \]

(11)

where \( \Phi_{S_\downarrow} \) and \( \Phi_{L_\downarrow} \) are the downward shortwave and longwave irradiances; \( a \) and \( e \) are whole-surface albedo and emissivity, respectively; \( \sigma \) is the Stefan-Boltzmann constant; \( T_a \) [degK] is the air temperature at a reference height; \( G_a \) is the aerodynamic conductance; \( G_r = 4 \varepsilon \sigma T_a^3 / (\rho \alpha c_{PA}) \) is the radiative conductance; \( \rho \) is the density of air \( c_{PA} \) is the specific heat of air at constant pressure.

In actual model coding, the energy fluxes (denoted \( \Phi \) above) and mass fluxes (denoted \( F \)) are calculated separately for the day (sunlit) and night parts of each 24-hour day, and then summed.

(3) **Soil evaporation** \( (F_{WS}) \) is given by

\[
F_{WS} = (1-v) w^\beta F_w \text{(PT)}
\]

(12)

where \( \beta \) is an exponent specifying the rate of decrease of soil evaporation with decreasing relative soil water \( w \).

(4) **Runoff** \( (F_{WR}) \) is given by

\[
F_{WR} = F_{WP} \text{Step}(w-1)
\]

(13)

so that \( F_{WR} = F_{WP} \) (all precipitation runs off) when the soil is saturated \( (w = 1) \), and there is no runoff otherwise.

(5) **Deep drainage** \( (F_{WD}) \) is given by

\[
F_{WD} = k_D Z_{w} w^\gamma
\]

(14)
where $\gamma$ is an exponent specifying the rate of decrease of deep drainage with decreasing relative soil water $w$, and $k_D$ is a rate [day$^{-1}$] for the depletion of soil water by deep drainage.

**Phenomenological Equations for Carbon Fluxes**

In Equation (4), the phenomenological equation for the plant carbon production flux or net primary productivity ($F_{CP}$) is

$$F_{CP} = \left[ (\alpha_Q v F_Q)^{-1} + (\alpha_W \rho_W F_{WT})^{-1} \right]^{-1} \tag{15}$$

where $F_Q$ is the incident quantum flux of photosynthetically active radiation (PAR) on the surface [mol-quanta m$^{-2}$ day$^{-1}$], and $\alpha_Q$ and $\alpha_W$ are respectively a PAR use efficiency [molC mol-quanta$^{-1}$] and a transpired-water use efficiency [molC mol-water$^{-1}$]. The leaf allocation coefficient responds to soil water through

$$a_L = \frac{\sqrt{w}}{\sqrt{w} + \sqrt{w_0}} \tag{16}$$

where $w_0$ is the relative soil water at which $a_L = 0.5$. Equations (15) and (16) are taken from a recent analysis of carbon allocation using ecological optimality principles (Raupach 2005).
Appendix B: Observation Model

This Appendix summarises the equations currently used in the WaterDyn observation model (April 2007, WaterrDyn17M). Some aspects of the observation model are placeholders only and will be revised.

(1) Normalised Difference Vegetation Index (NDVI): The NDVI ($N$) is assumed to be linearly related to the green-leaf cover fraction ($v$), through

$$N = N_0 + v \frac{N - N_0}{N_1 - N_0}$$  \hspace{1cm} (17)

where $N_0$ and $N_1$ are NDVI values for bare soil and full canopy cover, respectively.

(2) Land Surface Temperature (LST): The observation model for LST ($T_s$) needs to take into account the difference between conditions at time of satellite overpass ($t_p$) and the average diurnal conditions described by the dynamic model (Appendix B). We first relate $T_s$ at time $t_p$ to the air temperature and sensible heat flux ($\Phi_H$) at that time:

$$T_s(t_p) = T_a(t_p) + \frac{\Phi_H(t_p)}{\rho_a c_p G_a(t_p)}$$  \hspace{1cm} (18)

The instantaneous ($t_p$) values of $\Phi_H$ and $T_a$ can be related to model (diurnally averaged) values through the following simple, empirical assumptions:

$$\Phi_H(t_p) = \Phi_H(\text{diurnal average}) \max \left\{ 2 \cos \left( \frac{\pi (t_p - t_{\text{noon}})}{t_{\text{dusk}} - t_{\text{dawn}}} \right), 0 \right\}$$  \hspace{1cm} (19)

$$T_a(t_p) = 0.5(T_{a\max} + T_{a\min}) + 0.5(T_{a\max} - T_{a\min}) \cos \left( \frac{\pi (t_{Ta\max} - t_p)}{2(t_{Ta\max} - t_{\text{dawn}})} \right)$$  \hspace{1cm} (20)

where $t_{Ta\max}$ is the time of maximum temperature in the day, and $t_{\text{dawn}}, t_{\text{noon}}$ and $t_{\text{dusk}}$ are respectively the times of dawn, noon and dusk. Equation (19) assumes that the time course of heat flux is a cosine curve, zero at dawn and dusk and maximal at noon. Equation (20) assumes that minimum air temperature occurs at dawn, maximum at a specified time $t_{Ta\max}$, and that the trajectory of temperature during the day is cosinusoidal (but not in phase with heat flux).

Finally, the (diurnally averaged) sensible heat flux is related to the other energy fluxes in the surface energy balance, as

$$\Phi_A^* = \Phi_E + \frac{\Phi_H}{p}$$  \hspace{1cm} (21)
where notation follows Appendix B. Thus $T_d(t_p)$ is expressible in terms of the latent heat flux, and thence the total evaporation, since

$$\Phi_E = \rho_w \lambda_w (F_{WT} + F_{WS})$$

(22)

The end result is an expression for $T_s(t_p)$ in terms of meteorological forcing variables, diurnally averaged fluxes and state variables available to the dynamic model.

(2) **Catchment outflow at monthly scale:** Initially, this is described as the sum over a month and a catchment area of the surface runoff and drainage from the lower soil layer, for each land element in the catchment:

$$\text{Catchment Outflow} = \int_{\text{month}} dt \sum_{\text{catchment}} (F_{WR} + F_{WD2})$$

(23)

To avoid difficulties with water extractions from rivers (farm dams, irrigation, offtakes etc) we use only data from nominally unimpaired catchments as identified by Francis Chiew (CSIRO Land and Water and e-Water CRC). These are small catchments for which lags between elemental-area water fluxes and catchment outflow can be assumed to be not significant at monthly time scale.
Appendix C: Land Surface Temperature algorithm

Land surface temperature (LST) estimation from infrared satellite data is problematic due mainly to atmospheric composition (particularly the water vapour component) and the emissivity of the Earth’s surface (Prata 1993; Prata 1994). Of these, emissivity is the larger error source as it can be highly spatially and temporally variable because it is dependent on the type, condition and mix of land cover (see below for justification).

Advances have been made in developing algorithms that calculate an LST that is representative of the pixel size of the satellite data. For AVHRR the approach is the so-called “split-window” method where the differential absorption between two closely spaced channels is used to assess and correct for the water vapour content of the atmosphere. The split-window algorithm used in this work is (Sobrino and Raissouni 2000):

\[
\text{LST} = T_{11} + 1.40(T_{11} - T_{12}) + 0.32(T_{11} - T_{12})^2 \\
+ 0.83 + (57 - 5W)(1 - \varepsilon) - (161 - 30W)\Delta\varepsilon
\]  

(24)

where \(T_{11}\) and \(T_{12}\) are the brightness temperatures in the 11 and 12 micron channels, \(W\) is the precipitable water content of the atmosphere (in g cm\(^{-2}\) or cm liquid water), \(\varepsilon\) is the channel-average emissivity and \(\Delta\varepsilon\) is the difference between channel emissivities. The emissivity and \(\Delta\varepsilon\) are obtained by consideration of whether the surface is bare soil, partially vegetated or fully vegetated, as determined from the NDVI (following Sobrino and Raissouni 2000). In principle the water vapour can be derived from the data themselves but in practice this proves to be a relatively noisy determination. Until we have refined this method, the value of \(W\) is interpolated from the NCEP 2.5 degree 6 hourly global reanalysis fields (Kalnay et al. 1996).

For AATSR, an optimised split-window algorithm is (Coll et al. 2006):

\[
\text{LST} = T_{11N} + 0.04 + 0.94(T_{11N} - T_{12N}) + 0.25(T_{11N} - T_{12N})^2 \\
+ 45(1 - \varepsilon) - 55\Delta\varepsilon
\]  

(25)

where \(T_{11N}\) and \(T_{12N}\) are the 11 and 12 nadir micron channels, and again \(\varepsilon\) is the channel-average emissivity and \(\Delta\varepsilon\) is the difference between channel emissivities. Simulation studies (Coll et al. 2006) show that this algorithm has little sensitivity to atmospheric precipitable water (a 1 cm increase caused a decrease in estimated LST of less than 1°C), but that an uncertainty in surface emissivity of ±0.005 resulted in an uncertainty in LST of ±0.4 degC.

For determination of AATSR LST we use the quadratic coefficients in Equation (25), but we calculate \(\varepsilon\) and \(\Delta\varepsilon\) by the same (Sobrino and Raissouni) method used for AVHRR. The AVHRR NDVI-based thresholds for these fractional cover types were scaled by the ratio of maximum AATSR NDVI to maximum AVHRR NDVI. Our NDVI estimates are taken from monthly composites of both AATSR and AVHRR over Australia in 2003 (Paget and King 2005). The minimum AATSR NDVI used in present \(\varepsilon\) and \(\Delta\varepsilon\) calculations is 0.03 and the maximum is 0.75.
Appendix D: Remote Sensing Data Sources

This section summarises information on several remote sensing data sources used here. These include data from the following sensors: (1) NOAA-AVHRR; (2) MODIS, (3) SeaWiFS, (4) SPOT-VGT and (5) AATSR. Of these, the NOAA time series is the only one operationally supported for the next decade. In addition we have used data from (6) the GlobCarbon project, a compilation by the European Space Agency of satellite-based vegetation data from several sources. Details are summarised in Table 1.

**NOAA-AVHRR:** The NOAA polar-orbiting satellites have carried AVHRR instruments operationally since the launch of NOAA-6 in 1979. The AVHRR sensor records data in 5 spectral bands of the electromagnetic spectrum: (1) red (580-680 nm); (2) Near Infrared (NIR) (725-1100 nm); (3) 3.55-3.93 μm; (4) 10.5-11.3 μm; and (5) 11.5-12.5 μm. The spacecraft are in sun-synchronous polar orbits of approximately 100 min duration at an altitude of about 700km. Each orbit comprises an ascending and a descending component corresponding to whether the spacecraft is travelling northwards or southwards respectively. The overpass time of the ascending node is nominally around 1330 local solar time but changes slowly with orbital drift (typically at 0.25 to 0.5 h/y). The spatial resolution of AVHRR data is 1.1 km at nadir (the point directly beneath the satellite), increasing to 5.4 km at the edge of the swath where the scan angle is 55°. For details see Cracknell 1997.

The CSIRO AVHRR archive is maintained by CSIRO Marine and Atmospheric Research. Between 1981 and 1986 the basic data are coarse-resolution (about 8 km at nadir) Global Area Coverage (GAC) data Cracknell 1997 provided by NOAA. These data are also used to supplement the limited full resolution data from 1986 until 1992 when the data began to be comprehensively archived from direct broadcasts from the NOAA satellites received in Australia. Since 1992, the data from a number of Australian reception stations have been combined by stitching the different segments from each station to eliminate redundancy and produce a single best-quality scene for each overpass (King 2000; Lovell et al. 2003; King 2003). The daily coverage in this archive is an area of approximately 50 million km², including the entire Australian land surface and surrounding regions to at least 2000km from the Australian coast. Since 1992, coverage of this area has been obtained four times daily.

The Australian AVHRR archive is available in two forms, both used in this work.

1. The "BPAL AVHRR" archive has been compiled from various sources and processed to produce complete, cloud-free, calibrated, geolocated, continental coverage of all AVHRR channels as seen by the afternoon overpass, at 0.05 degree (about 5 km) spatial resolution, covering land only, for 1981 to present. Compositing (maximum-NDVI), to approximately 10-day time resolution, was used as a first-order means of removing cloud effects. Additional "BISE" (Best Index Slope Extraction) filtering was used to further reduce cloud contamination and the effects of variations in view and sun angles (Lovell and Graetz 2001). The "BPAL" terminology arises because this archive extends a series available from NASA for the period 1981-1994 called the PAL (Pathfinder AVHRR Land) dataset, using BISE filtering. The BPAL AVHRR archive is used here for analysis of land condition.
2. The "CATS" (CSIRO AVHRR Time Series) archive is currently available from 1992 to present. This archive includes all AVHRR channels at a nominal spatial resolution of 1.1 km at nadir and temporal resolution of up to four overpasses per day. The data are calibrated and geolocated, with other processing in several versions described in Table B2.

**MODIS:** The Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument aboard the Terra and Aqua satellites, launched in December 1999 and March 2002, respectively. The orbit of Terra around the Earth is timed so that it passes from north to south in the morning (about 1030 local solar time), while Aqua passes south to north in the afternoon (about 1330 local solar time). Terra MODIS and Aqua MODIS each view the entire Earth surface every day, acquiring data in 36 spectral bands ranging from 405 nm to 14.4 µm. The spatial resolution of MODIS data is 250 m for one spectral band in the visible and one in the NIR, 500 m in 5 visible to mid-infrared bands and 1000 m in all other bands. The data used in this study are standard global products obtained from NASA by DLT tapes (due to the enormous amount of data) and subsequently uploaded to the CSIRO MODIS Data Storage Cluster. These standard products may also be downloaded by FTP from the NASA website.

**SeaWiFS:** The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is carried on the SeaStar satellite launched on August 1, 1997 as part of NASA’s "Mission to Planet Earth". The SeaStar maintains a sun-synchronous 705 km altitude orbit, with a north-to-south equatorial crossing at 12:20 local solar time, covering the Earth’s surface once a day. The SeaWiFS sensor has 8 bands in the 402 nm (violet) to 885 nm (NIR) range. It differs from the AVHRR sensor in that it can tilt to avoid sunglint on the sea. SeaWiFS transmits local area coverage (LAC) data in real-time at a spatial resolution of 1.1 km, with global area coverage (GAC) data archived and transmitted at 4.5 km resolution. The data used in this project are the SeaWiFS level 3 monthly NDVI product at 4.5 km resolution. Information about the SeaWiFS project can be obtained from http://oceancolor.gsfc.nasa.gov/SeaWiFS/

**SPOT-VGT:** The "Vegetation" (VGT) instrument is a wide-field sensor carried as part of the SPOT 4 and 5 satellite payloads launched on March 24, 1998 and May 4, 2002. The SPOT 4/5 satellites maintain a sun-synchronous polar orbit at ~830 km altitude. The Vegetation instrument has 4 non-contiguous bands in the visible, NIR, and MIR range (430-1750 nm), with a swath width of 2250 km at 1.165 km spatial resolution, allowing 90% global coverage in one day. Several products are available, including daily and ten-day synthesis products (S10) at full resolution as well as 4 km and 8 km reduced resolutions. The VGT images are processed and archived by the Belgian research institute VITO. The data used in this project are the SPOT VGT-S10 NDVI series at 1 km resolution.

**AATSR:** The Advanced Along Track Scanning Radiometer is a 1km resolution sensor with a relatively narrow (512 km) swath carried on ESA’s ENVISAT platform in a sun synchronous polar orbit with an overpass time of 1030 and a revisit time of 35 days. Although three overpasses a day cover Australia, the narrowness of the swath means that complete coverage is only obtained every several days. The sensor has 7 bands ranging from the visible through to the thermal infra-red; in particular it has 11 and 12 micron bands that match those of the AVHRR sensor. Two key characteristics of AATSR are the high quality of its thermal calibration, and that it uses a conical scan to obtain a dual view of the swath, thereby allowing improved correction for angular and atmospheric effects. AATSR is a successor instrument to ATSR and
ATSR2 which were flown on earlier ESA missions. The Top Of Atmosphere L1B product has been used here to derive Land Surface Temperature measurements from the 1km brightness temperature channels. Gridded LSTs are available from ESA, but only aggregated to lower spatial resolution. We are investigating the possibility of operational inclusion of these data in near real time.

**GlobCarbon:** The GlobCarbon project is part of the Global Terrestrial Observing System coordinated by the FAO. GlobCarbon uses data supplied by the European Space Agency to produce a range of fully calibrated satellite estimates of global land surface properties (fire, albedo, fAPAR, LAI, vegetation growth cycle) which are nearly independent of the original data source. The focus of the project is on the seven years 1997 to 2003, a period of overlap between various satellite measurements. GlobCarbon products and services are managed by VITO and various other European agencies, and distributed by VITO at [http://geofront.vgt.vito.be/geosuccess/](http://geofront.vgt.vito.be/geosuccess/). The GlobCarbon data available for this project were monthly LAI from 1999 to 2002, generated from SPOT VGT and ATSR data.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Agency (Country)</th>
<th>Platform (Launch)</th>
<th>Swath (km)</th>
<th>Revisit time (overpass time)</th>
<th>Spectral Bands</th>
<th>Nadir spatial resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVHRR</td>
<td>NOAA (numerous satellites)</td>
<td>2500</td>
<td>1 day (nominal: 0900, 1400)</td>
<td>5 bands (visible, NIR, thermal)</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>MODIS</td>
<td>NASA (USA)</td>
<td>Terra (Dec 1999) / Aqua (May 2002)</td>
<td>2330</td>
<td>1-2 days (Terra: 1030) (Aqua: 1330)</td>
<td>36 bands (visible, NIR, MIR, thermal)</td>
<td>250 to 1000</td>
</tr>
<tr>
<td>SeaWiFS</td>
<td>NASA (USA)</td>
<td>SeaStar (Aug 1997)</td>
<td>2801 (LAC), 1502 (GAC)</td>
<td>1 day (1220)</td>
<td>8 bands (visible, NIR)</td>
<td>1100 (LAC) 4500 (GAC)</td>
</tr>
<tr>
<td>VGT</td>
<td>CNES (France)</td>
<td>SPOT 4 / 5 (Mar 1998 / May 2002)</td>
<td>2250</td>
<td>1-2 days</td>
<td>4 bands (visible, NIR, MIR)</td>
<td>1165</td>
</tr>
<tr>
<td>AATSR</td>
<td>ESA</td>
<td>Envisat (2002/02)</td>
<td>512</td>
<td>35 days (1030)</td>
<td>7 bands (visible, SWIR, MIR, thermal)</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 1: Details of satellite sensors providing data utilised in this work
Appendix E: Operational System

Overview: Figure 10 gives a conceptual flow diagram of the AWAP prototype operational system (http://www.eoc.csiro.au/awap/). The system runs on a weekly basis to provide near-real-time estimates of continental soil moisture and water fluxes, averaged over the previous week.

For operation in forward mode (without data assimilation), the operational system carries out the following basic steps:

11. Download gridded daily meteorological forcing data (rainfall, solar radiation, maximum and minimum temperature) from the Bureau of Meteorology (BoM). These data are generated operationally by a companion AWAP project.

12. Apply quality assurance checks to BoM meteorological forcing data.

13. Obtain assimilation data as available: satellite imagery of vegetation greenness (AVHRR-NDVI) and surface temperatures (AVHRR), and catchment discharge data from unimpaired, gauged catchments. (In forward mode these data are passed through the model for comparisons with output, but not assimilated).

14. Obtain model initial conditions, from the end of previous run.

15. Set model parameters.

16. Run the WaterDyn model for 1 week, producing daily and weekly-averaged output.


18. Convert model output to Arcview-compatible form suitable for transfer to clients, and to graphical forms suitable for web-based display.

19. Update the web interface.

20. Update archives, logging and run documentation files.

Hardware: Two DELL 2950 servers, each with two Dual-core processors, 8GB of ram and 1.5TB of RAID5 disk have been purchased and installed to support the project. These have been configured in parallel to provide simultaneous operational and development systems, with the development system being available to take over immediately in the event of a compromise to the operational machine. Data required for each run are hosted on a number of other servers within CMAR and are archived separately.

Software: The software comprises the WaterDyn model itself, data filters to process spatial input data (daily meteorological fields, satellite observations) into the format required by the model, and an output processor to convert and analyse the results of the model run. Additional code, in the form of multiple Perl scripts, is used to integrate these programs, pull data from network servers, log run parameters and anomalies, archive outputs, and push results to the presentation server. A standardised, automated directory structure is used to manage inputs, outputs, archival and documentation.
The data streams obtained in near real time are as follows.

1. **Meteorological data**: These are provided by BoM from their website. Since mid-March 2007, daily fields for rainfall, maximum and minimum temperature have been automatically downloaded, reformatted and stored in a local archive on a daily basis. More recently daily solar radiation has been provided. This process is running smoothly, although few file format issues are still being resolved with BoM. A script to automatically select, reformat and ingest these data for input to the model has been developed.

2. **AVHRR data**: The NOAA AVHRR instrument provides continental observations of brightness temperature (BT) several times daily. BoM are providing the AVHRR data feed. In CMAR we are developing algorithms to compute land surface temperature (LST) from BT, and are providing support to the BoM with base processing software (CAPS), compositing code, and a system to provide enhanced quality base data in near real time. A 15 year time series of AVHRR BT data has been processed and converted to LST for model testing. It has also been used to successfully develop the ingest pathway for the near real time data feed. A near real time source of atmospheric precipitable water is needed for the LST algorithm. Presently this is obtained from the NCEP global analysis.

3. **AATSR data**: The Advanced Along Track Scanning Radiometer provides highly accurate brightness temperature measurements with continental coverage every three days. We have implemented an LST algorithm and processed an historical time series of 3 years of AATSR data for use in the model testing and development. It is ingested into the model by an almost identical route to the AVHRR. We have been experimenting with accessing AATSR data in near real time via the internet from Europe. This was working until recently until something changed on the server. We are working with ESA to restore this data source.

4. **MODIS**: Daily fields of LST are produced by the Land Processes DAAC in the USA. We have automated the process of downloading the 17 separate tiles required to cover Australia each day. Scripts have been developed and tested to mosaic, remap and reformat these tiles into continental fields suitable for ingest into the model. These operations will be coupled with the downloading step to automate the whole process.

5. **Runoff**: Stream runoff data is available for many catchments historically. It is possible that the CSIRO Water Resources Observation Network and/or the BoM water monitoring initiative will be able to provide these data in near real time. If so, the model can use them and they will be ingested.

**Outputs**: The output of the model runs is archived for three purposes: (1) as input to the next run, (2) documentation purposes, and (3) for delivery to BRS. An externally accessible FTP server is in place to enable delivery. As the model development is still continuing and the operational directory structure evolves, it has not yet been practical to automate this stage of the process, though it is under active consideration.
Appendix F: Specification of CMAR contribution to AWAP (2006-07)

The following specifications are reproduced from the AWAP WorkPlan 2006-2007, Version 1.1, 6 June 2006, as Attachment A to the Collaborative Research and Development Agreement signed June 2006.

**Goals**

- To develop a system to determine the terrestrial water reserve (water in soils and plants) for Australia, combining model and observations using model-data fusion methods.

- To apply this system to establish the past climatology and time-evolving present state of the terrestrial water reserve and its controlling fluxes (precipitation, transpiration, soil evaporation, runoff, drainage), at continental scale.

- To provide a demonstration system for operational, near-real-time assessment of Australian water availability. This system will deliver near-real-time estimates (including uncertainties) of soil moisture and water fluxes (precipitation, transpiration, soil evaporation, runoff, drainage) with continental coverage, 5 km spatial resolution and weekly time steps, so that estimates are available with a maximum time delay of one week from the end of each weekly assessment period.

- To include remotely sensed land surface temperature as an assimilated variable in the model-data fusion system for determining the terrestrial water reserve, on a trial basis over a limited area defined by the Murrumbidgee basin.

**Contribution**

1. **DYNAMIC MODEL DEVELOPMENT:**
   
   Further develop the dynamic model. This is the central terrestrial biosphere model for water, carbon and vegetation dynamics. It will be based on existing models used in predecessor projects (Australian Water Availability Project 2005-06). The dynamic model predicts the evolution of hydrological state variables including soil moistures, fluxes (transpiration, soil evaporation, drainage / recharge, runoff) and vegetation state, using driving meteorological data and ancillary static data. Of particular concern are the model components for prognosing vegetation state variables such as leaf area index.

2. **DATA COLLATION AND CURATION:**
   
   (a) Acquire remotely sensed data using existing sources. Sensors will include AVHRR, supplemented by SeaWifs for validation and ATSR series for surface temperature.

   (b) Develop and evaluate "observation models" for remotely sensed data: These predict remote-sensing observations from state variables in the dynamic model.

   (c) Acquire and evaluate time series of ground-based hydrological data [streamflow, groundwater levels, etc] from existing sources.

   (d) Acquire driving meteorological data with suitable properties in space (continental scale, 5 km resolution) and time (multi-decadal records, daily resolution). Fields required
include rainfall, radiation, maximum and minimum daily temperatures, and (depending on upgrades to dynamic model) humidity. Suitable data are already available from the Bureau of Meteorology component of AWAP.

(f) Acquire ancillary static data sets (soil, topography, vegetation cover type, land use).

3. MODEL-DATA FUSION:

(a) Further develop a model-data fusion scheme for applying multiple data constraints to the dynamic model, based on sequential data assimilation with the Ensemble Kalman Filter (EnKF).

(b) Improve the uncertainty estimates yielded by the EnKF, by investigating and incorporating appropriate trade-offs between model and observation error. A key point about the data assimilation approach is quantification of uncertainty in predictions, arising from uncertainty in climate or management scenarios, data errors or errors in predictive models. This is an essential component of risk assessment. Missing data (remotely sensed or ground based) do not invalidate predictions, but rather increase their uncertainties.

**Deliverables**

- **Capability to determine soil moisture and terrestrial water balance fluxes (transpiration, soil evaporation, runoff, drainage, with rainfall as input) at fine space and time scales (daily, 5 km over Australia), using a model-data fusion (data assimilation) approach with in-situ (streamflow, other WRON) and remotely sensed data;**

- **Climatological histories for soil moisture and water balance fluxes, to locate present states and trends in a climatological context;**

- **A demonstration system for operational, near-real-time assessment of Australian water availability. This system will deliver near-real-time estimates (including uncertainties) of soil moisture and water fluxes (precipitation, transpiration, soil evaporation, runoff, drainage) with continental coverage, 5 km spatial resolution and weekly time steps, so that estimates are available with a maximum time delay of one week from the end of each weekly assessment period. Delivery will be by download from BRS of spatial data provided weekly on a suitable CSIRO server.**

**Project Timeframe**

The timeframe for this component of the project encompasses Financial Year 2006-2007 operating under a collaborative agreement between the Bureau of Rural Sciences and the CSIRO.

**Explanatory notes**

The terrestrial water reserve (water in soils and plants) is the dominant water resource for ecosystems and dryland farming systems; for all riverine and groundwater systems; and thence for urban and irrigation water supplies. For this reason, terrestrial water is a pressure point for economic, environmental and social development in Australia: its absence is one of the most important signs of drought. Observation of terrestrial water is therefore a critical because of its importance for ecosystems and farming systems and because the terrestrial water store is the link
between weather, climate and rainfall and the consequent large variability in riverine and groundwater supplies. Information is needed:

1. For the past – to understand the effects on water resources of past variability and trends in climate, and to separate the influences of climate and human management;

2. For the present – to have the best possible information about the current state and behaviour of terrestrial (and related) water systems;

3. For the future – to provide probability-based forecasts of fluctuations in water supply, particularly from climate variations and trends over time scales from days to decades, so that management for improved overall benefits can be effective.

Observations are needed at regional and continental scales for two reasons, the first being the spatial connectedness of water systems (basins and catchments, e.g. the Murray-Darling Basin or the Great Artesian Basin). Secondly, economic and social connectivity reaches over even larger scales: the economic and social factors which influence patterns of water use in a region stem from national-scale (and international-scale) forces, including not only market-driven supply and demand for commodities but also the water availabilities in distant regions which affect this supply and demand. Hence there is a critical need for a national / continental focus.

**Milestones and Payment Schedule**

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<th>on signing of MOU</th>
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<td>AWAP 07 - Climatological history to at least 1980 for soil moisture and water balance fluxes (transpiration, soil evaporation, runoff, drainage, with rainfall as input) at fine space and time scales (weekly and monthly 5 km over Australia).</td>
<td>01 April 2007</td>
<td>$25,000</td>
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<td>AWAP 08 - Final report of a near-real-time operational system for deriving weekly and monthly soil moisture and water balance fluxes over Australia at 5km resolution.</td>
<td>30 June 2007</td>
<td>$25,000</td>
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<tr>
<td>AWAP 09 - Near-real-time operational system deriving weekly and monthly soil moisture and water balance fluxes over Australia at 5km resolution.</td>
<td>30 June 2007</td>
<td>$25,000</td>
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Figures

Figure 1: Schematic representation of components of a hydrological and terrestrial-biosphere data assimilation system. Upper panel: without data assimilation; lower panel: with data assimilation.
Figure 2: Spatially averaged monthly time series over the whole Australian continent for a 26-year run of the forward model. The time axis ($t = 0$ to 26 years) runs from 1-jan-1981 to 31-dec-2006. Top panel: meteorological forcing; second panel: model output of state variables, the relative soil moisture in two layers ($w_{1,2}$) and green-leaf carbon store $C_L$ (molC m$^{-2}$); third and fourth panels: model output of water balance terms including contributions to evapotranspiration (third panel) and contributions to outflows (fourth panel). Model version and run: WaterDyn18M, Australia18a.
Figure 3: 26-year time series (1981-2006) of monthly upper-layer relative soil moisture for Australia. Meteorological forcing data: SILO. Model version and run: WaterDyn18M, Australia18a.
Figure 4: 26-year time series (1981-2006) of percentile rank of monthly upper-layer relative soil moisture for Australia. Meteorological forcing data: SILO. Model version and run: WaterDyn18M, Australia18a.
Figure 5: Location of unimpaired catchments in South Eastern Australia (hatched red areas), superimposed on the spatial domain map (Figure 6). The Murrumbidgee basin (410) is stippled in black.
Figure 6: Predicted versus observed discharge for 200 gauged unimpaired catchments across Australia. Left and right panels show the same comparison on linear and logarithmic axes, respectively. Model version and run: WaterDyn17M, Australia17a.
Figure 7: Land surface temperatures from AVHRR (NOAA16) and AATSR, on three successive days in summer (3-5 Jan 2004) (upper panel) and two days in winter (15 and 16 Jul 2004). Times are in UTC, approximately 10 hours behind local solar time in eastern Australia. The AVHRR (NOAA16) overpass occurs in mid-afternoon and the AATSR overpass in mid-morning.
Figure 8: Comparison of modelled and observed (AVHRR-NOAA16) land-surface temperature at satellite overpass time, averaged across the Murrumbidgee basin, for 2003 and 2004. Model version and run: WaterDyn17M, Murrumbidgee17b.
Figure 9: Comparison of modelled and observed (AATSR) land-surface temperature at satellite overpass time, averaged across the Murrumbidgee basin, for 2003 and 2004. Model version and run: WaterDyn17M, Murrumbidgee17a.
Figure 10: Flow diagram of prototype operational system.
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