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Review of water models and their application in Australia

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Foreword

Water issues are now considered among the most important drivers and limitations for natural resource management in Australia. This includes management of biodiversity, primary production and environmental hazards like salinity and drought, through to urban and rural water supplies. A better understanding of water availability is needed across the entire continent, and is relevant to the implementation of key government policies such as Exceptional Circumstances and the National Water Initiative (NWI).

In 2004, the Bureau of Rural Sciences (BRS) recognised that Australia had no comprehensive and consistent source of information on the dynamic water balance, that is, on the spatial and temporal relationships between rainfall, evaporation, transpiration, drainage to ground and surface water, and runoff to rivers and storages. Addressing this fundamental knowledge gap became the primary focus of a project known as Water 2010.

Water 2010 is a BRS driven research collaboration designed to address the information needs of the National Water Commission (NWC), and to support the Department of Agriculture, Fisheries and Forestry (DAFF) in developing sound water policy. The project is designed to capture information on the water balance at a variety of scales, investigate the consequences for water resources of likely or desired changes in land use, population growth, climate and water policies and practices, and then examine the potential impacts of these scenarios on communities, industries and regions to identify the challenges for industries and regions and suggest opportunities and trade-offs.

Modelling the dynamics of the whole water cycle at a national scale with the capacity to understand and model land cover and land use effects on the water balance was recognised as being critical to this work. It was realised that to effectively attempt this, a comprehensive review of water balance models used in Australia was needed in the first instance. This paper presents just such a review. It considers what data are currently available for national scale water balance modelling and describes existing water balance models in terms of their complexity, their performance under various conditions and their limitations. In particular, models are examined in relation to their ability to use and output spatial data, their currency, data requirements and national applicability.

This paper is the first in a series of Technical Papers describing the progress and outputs of the Water 2010 project. BRS gratefully acknowledges the support of DAFF and the NWC in this Australian Government work.

Dr Colin J. Grant
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Executive summary

Water balance models play many roles in agriculture and natural resource management

Agriculture is the highest consumer of water resources in Australia. Water balance models play a vital role in agriculture in terms of estimating water use, water allocation and current water status at a given scale. Most of the models developed are purpose-specific and suitable for application at a given spatial scale.

A comprehensive review of the application and performance of models is given here

This report reviews widely-used water balance models developed in Australia over the last three to four decades that have been utilised for simulating water balance status at various temporal and spatial scales. A comprehensive review of the application of these water balance models is provided, supported by assessments of individual model performance. The limitations and assumptions made under various approaches to water balance modelling are subsequently examined.

Models reviewed are categorised in terms of their complexity

The models considered in this report are categorised in terms of their complexity with respect to the number of processes employed and their treatment of the soil profile. “Simple models” have a fixed number of soil layers and a bucketing approach to water inflows and outflows, while “complex models” seek to incorporate a continuous soil profile with a one- or two-dimensional flow.

Most complex models are point-based

Some complex models are spatial and applied at catchment scales

Simple models with a single soil layer often have the capacity to be applied at continental scales, while multi-layer simple models can be applied widely at regional or sub-regional scales. Most of the complex, one-dimensional water flow models reviewed are point-based. However, some complex, two-dimensional water flow models are spatial and are ideally applied at catchment scales.

Spatial models are increasingly being used in policy development

Research and policy agencies are focussing more and more on spatial modelling frameworks for natural resource management purposes, including water resource management. Models with a spatial capacity are therefore increasingly being used in the process of policy development.

Simple models are readily applied spatially but should seek to improve their biophysical processes

Developers of complex models, where wide-ranging application is normally hampered by lack of specific data, should be encouraged to simplify the model processes to facilitate accommodation into national spatial frameworks. Developers of simple models should be encouraged to improve the representation of biophysical processes, in line with new data sources, to gain more accurate predictions

Water balance information need

At present, there is no comprehensive and consistent source of national information on the water balance across Australia. ‘Water 2010 - national water balance information for policy and planning’ is a BRS/DAFF project that aims to address this fundamental knowledge gap. A national, spatially distributed water balance model is needed for this purpose.

Catchment water balance modelling approaches assessed

Six catchment-scale water balance modelling approaches were identified for further consideration in relation to the goals of Water 2010:

- BiosEquil / BiosEvolve
- AussieGRASS (GRASP)
- Australian Water Balance Model (AWBM)
- CATSALT
- TOPOG
- CLASS

These modelling approaches are briefly described in terms of input data requirements, model processes and runoff-related outputs, and then evaluated with respect to paradigm currency, data availability, model outputs, spatial flexibility and national applicability.

Paradigm currency

The six modelling approaches considered have been developed relatively recently (since the early 1990s) and continue to be actively researched and improved.

Input data availability

AWBM, AussieGRASS, CATSALT and CLASS require daily stream flow for calibration. These data are not available for all catchments in Australia.

Spatial flexibility

Four of the six modelling approaches investigated are spatially distributed and their outputs can be aggregated to different hydrological and management boundaries. However, complex models such as CLASS and TOPOG have considerable data requirements and are computationally demanding. AWBM is a lumped model and CATSALT is semi-distributed. They are less spatially flexible.

Model outputs

Most of the modelling approaches evaluated simulate evapotranspiration, runoff and deep drainage, but they vary in the level of detail and method of calculation. AWBM and CATSALT are the only models not able to model evapotranspiration. Only CATSALT, TOPOG and CLASS explicitly include flow routing procedures.

National application

Only BiosEquil and AussieGRASS have been applied at the national-scale.

Contents

Foreword **III**

Executive summary **IV**

Contents **1**

1. Introduction **2**

- 1.1 The BRS Water 2010 project and the National Water Initiative 2
- 1.2 Australian water balance models 4

2. Categorisation of water balance models **5**

- 2.1 Simple models with a bucketing approach 6
- 2.2 Complex models 10

3. Data requirements **13**

- 3.1 Simple models 13
- 3.2 Complex models 15

4. Data availability **24**

- 4.1 Meteorological data 24
- 4.2 Soil and soil hydraulic properties 29
- 4.3 Stream flow 31
- 4.4 Land use and vegetation 33
- 4.5 Irrigation 36
- 4.6 Hydrogeology 36
- 4.7 Water quality 38
- 4.8 Topography and hydrological mapping 38
- 4.9 Other 39

5. Model performance and limitations **40**

- 5.1 Single-layer simple models 40
- 5.2 Multiple-layer simple models 41
- 5.3 Limitations of simple models 42
- 5.4 Complex models 43
- 5.5 Limitations of complex models 45

6. Towards a modelling framework for Water 2010 **49**

- 6.1 Evaluation of modelling approaches 50

7. Conclusions **55**

8. References **57**

1. Introduction

Water issues are now considered among the most important drivers and limitations for natural resource management in Australia. This includes management of biodiversity, primary production and environmental hazards like salinity and drought, through to urban and rural water supplies. Agriculture consumes the largest volume of collected surface water, representing two-thirds of consumption in Australia (ABS 2000). This proportion is likely to increase when the water consumption by rain-fed agriculture is included in water accounts. Water supplies for farms have been impacted recently by declining water allocations brought on by more frequent droughts and less reliable effective rainfall. Thus, the ability to manage water use to gain sufficient yields and remain economically viable has become restricted. On the other hand, agriculture, as the largest water-consuming industry, has become the centre of promoting water conservation.

Water resources are crucial for Australia's economic, social and environmental wellbeing. The Australian Government in association with state and territory governments, with the exception of Western Australia, has announced a comprehensive strategy, known as the National Water Initiative (NWI), to improve water management across the country. This new initiative notes the imperative of increasing the productivity and efficiency of water use and the health of river and groundwater systems in Australia. Continuing to improve the productivity and efficiency of our water use is well recognised. Many research and policy frameworks are emerging that look to increase the efficiency of water use in agriculture, in which water balance models play a vital role.

1.1 The BRS Water 2010 project and the National Water Initiative

A better understanding of water availability is needed across the entire continent, and is relevant to the implementation of key government policies such as Exceptional Circumstances (EC) and the NWI. At present, Australia has no comprehensive and consistent source of information on the dynamic water balance, that is, on the spatial and temporal relationships between rainfall, evaporation, transpiration, drainage to ground and surface water, and runoff to rivers and storages. Addressing this fundamental knowledge gap is the primary focus of a collaborative BRS project known as Water 2010. The project is designed to address the information needs of the National Water Commission with respect to specific components of the NWI, and also to provide information needed by DAFF to develop sound water reform policy in a changing physical and social environment in Australia.

The specific provisions of the NWI that project is designed to address are:

Water access entitlements and planning framework

Water planning – sections 36-40

Water 2010 will assist in the preparation of statutory water plans for surface and groundwater management units in which entitlements are issued.

Addressing currently over allocated and/or overused systems – sections 41-45

Water 2010 will assist in defining allocations that provide a better balance in water use (including allocations to the environment) for all river systems and groundwater resources that have been over-allocated or are deemed to be stressed.

Assigning risks for changes in allocation – sections 46-51

Water 2010 will assist the government in quantifying and reducing the risk it bears as a result of a reduced or less reliable water allocation beyond 2014 arising from bona fide improvements in knowledge of the water systems' capacity to sustain particular extraction levels, and/or changes in government policy for new environmental objectives.

Parties to the NWI have agreed that an effective risk assignment framework can only occur in the context that:

- a new share-based water access entitlements framework has been established;
- water plans have been transparently developed to determine water allocation for the entitlements;
- regular reporting of progress with implementing plans is occurring; and,
- a pathway for dealing with known over-allocation and/or overuse has been agreed.

As a transparent, web-based analysis and reporting system, underpinned by state and territory data, Water 2010 will help ensure these contextual requirements of the risk assessment framework have been met.

Interception – sections 55-57

Water 2010 will assist in assessing the significance of water intercepting activities on catchments and aquifers based on an understanding of the total water cycle, and help monitor the progress of catchments and aquifers towards either full allocation or the threshold level of interception.

Water resource accounting

Consolidated water accounts – sections 82-83

Water 2010 will assist in the development and implementation of water resource accounts that can be reconciled annually and aggregated to produce a national water balance covering all significant water use, including groundwater systems, and considering landuse change, climate change and other externalities as elements of the water balance.

Information – section 86

Water 2010 will assist in the development of partnerships in data collection and storage.

Knowledge and capacity building

Section 101

Water 2010 will assist in identifying key knowledge and capacity building priorities needed to support ongoing implementation of the Agreement.

The project is not designed to address provisions in the NWI referred to under:

- Water markets and trading;
- Best practice water pricing;
- Integrated management of water for environmental and other public benefit outcomes;

- Urban water reform; and
- Community partnerships and adjustment.

This work is being variously covered, or is anticipated will be covered, by a number of agencies including the Australian Bureau of Agriculture and Resource Economics (ABARE), CSIRO, state Natural Resource Management (NRM) agencies, the Murray Darling Basin Commission (MDBC), catchment management authorities, regional water authorities, private consultants and local governments.

1.2 Australian water balance models

The development and use of mathematical models for simulating and predicting catchment water balances has proliferated during the past four decades. Generally, water balance models developed in Australia combine plant water use, water balance storage and water table fluctuations in varying degrees of complexity to predict current and future water balances and plant water availability. Although model choice should be made using a ‘horses for courses’ approach (CRC-CH 2000), it is sometimes confusing and difficult to choose the right water balance model for a specific purpose because the number of water balance models available is quite large.

It was realised that a comprehensive review of widely-used water balance models developed in Australia would be valuable for the Water 2010 project. Within this review, existing water balance models are analysed in terms of their complexity; their performance under various conditions and their limitations. In particular, models are examined in relation to their ability to use and output spatial data, as well as their currency, data requirements and national applicability.

The review does not explicitly cover salinity-related models, although a couple of salinity models are included because of their significance in water balance modelling. An overview of salinity models and modelling can be found in Littleboy *et al.* (2003).

2. Categorisation of water balance models

The development of numerous soil water and water balance models in Australia over the last three to four decades is evident from the literature. They range from physically-based models to empirically-based models. These models vary in terms of their degree of complexity, which is often determined by the specific purpose of the model development. It is therefore appropriate to categorise these models in terms of their complexity with respect to the number of processes employed and their treatment of the soil profile (Figure 1).

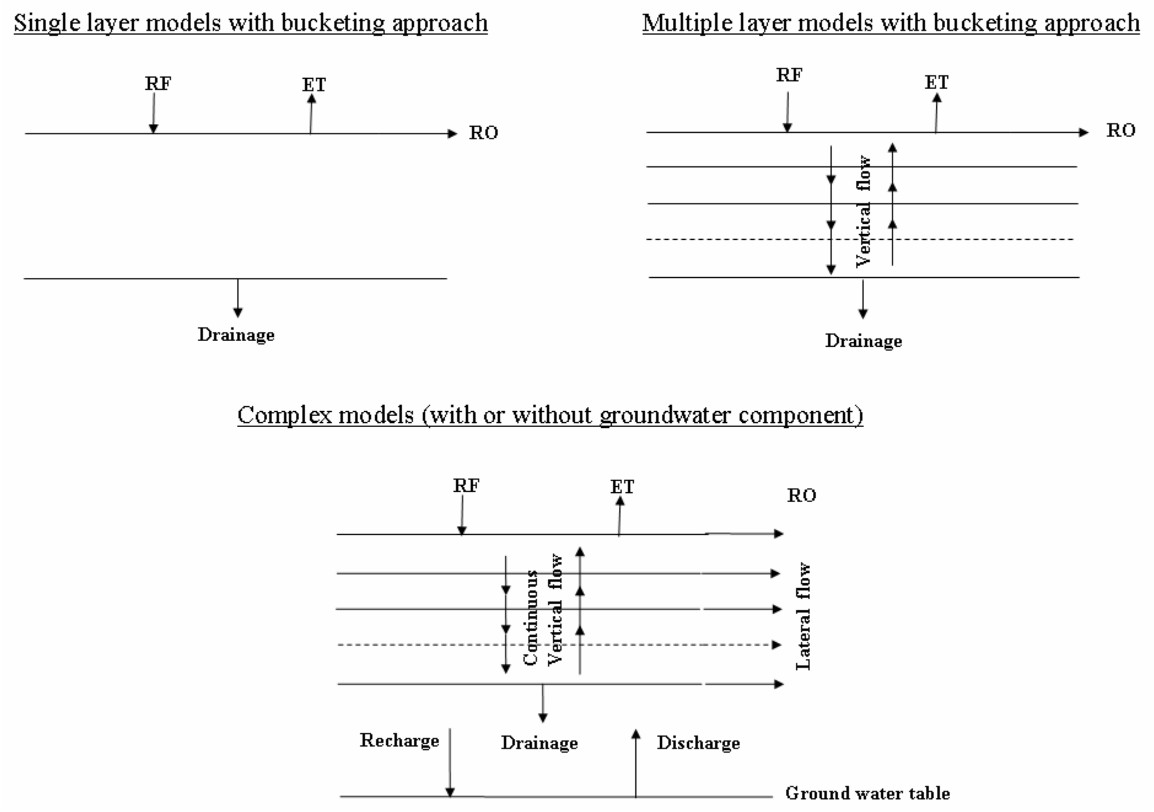

Figure 1 Schematic diagram for basic processes employed by each category of water balance models identified in this review. RF, ET and RO refer to rainfall, evapotranspiration (ET) and runoff

Water balance models considered in this report are categorised initially in terms of their complexity with respect to the number of processes employed. “Simple models” have a fixed number of soil layers and a bucketing approach to water inflows and outflows, while “complex models” seek to incorporate a continuous soil profile (Figure 2). Within the simple or fixed soil layer modelling category, models are divided into single layer or multiple layer approaches. In the complex, or continuous soil profile modelling category, models are considered more generally, but can be distinguished to some degree as one- or two-dimensional flow models.

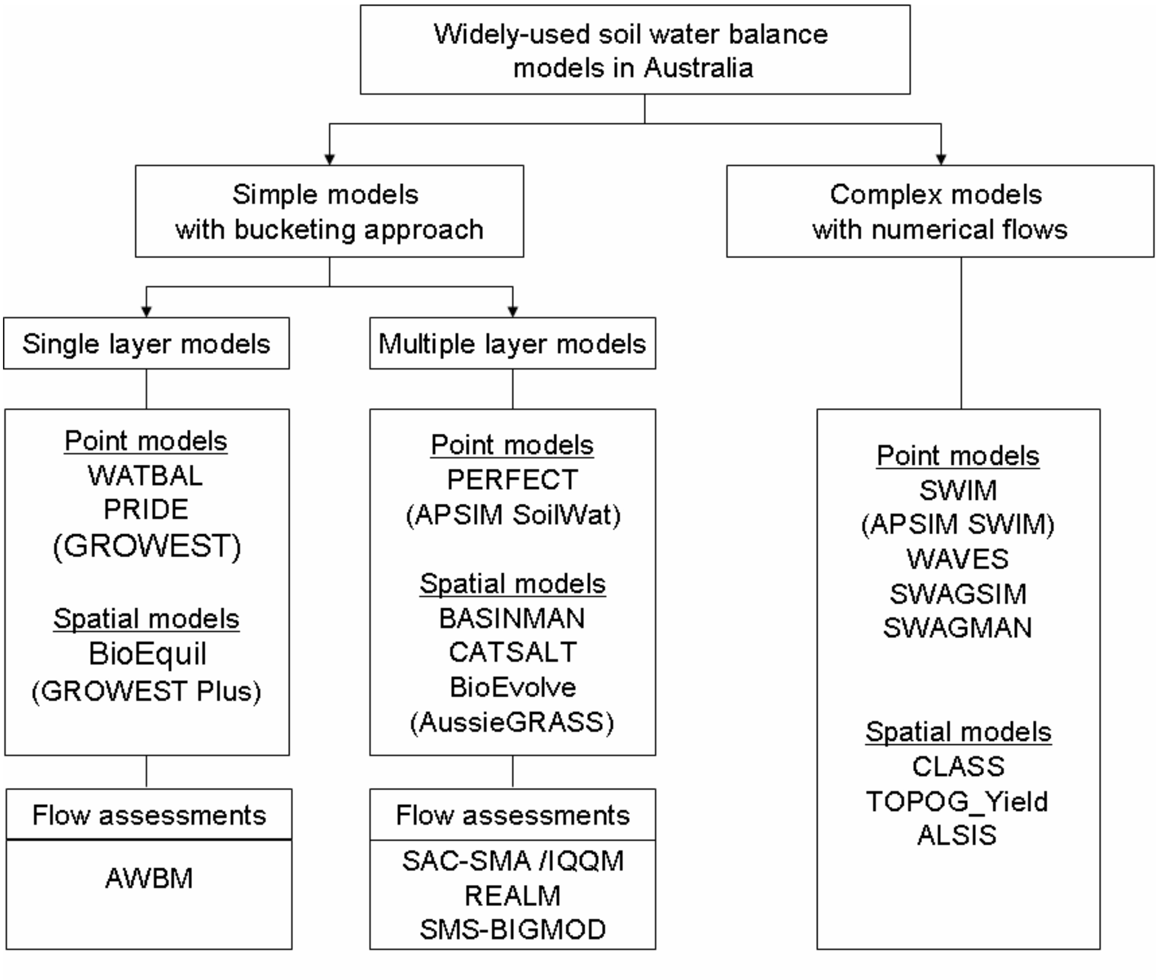

Figure 2 Widely-used soil water models developed in Australia. Models in brackets are mainly developed for other purposes; however they have soil water modules and can be used for soil water assessments

2.1 Simple models with a bucketing approach

In early versions of water balance models, the soil moisture was typically modelled as a simple bucket (Manabe 1969) that can be filled by precipitation and emptied by evaporation. Vegetation was not modelled explicitly and there was no distinction between evaporation and transpiration. When the bucket that represents soil or root zone of a plant or plant community is full, the excess precipitation leaves as surface runoff. Initial development of water balance models in this category assumed vertically and horizontally homogeneous soil, and thus the entire soil or root zone was represented as a single soil layer.

2.1.1 Single layer simple models

2.1.1.1 WATBAL

Single layer models assume that soil is vertically homogeneous. One of the early single layer models developed in Australia was WATBAL (Fitzpatrick and Nix 1968, Fitzpatrick *et al.* 1967, Keig and McAlpine 1974, McAlpine 1970) in which the moisture index proposed by Fitzpatrick and Nix (1970) was calculated. The moisture index is the ratio of predicted evapotranspiration (ET) to potential ET and can range in value from 0 to 1.0. A value of 0 indicates no water is available and a value of 1.0 indicates water is not limiting for plant growth. WATBAL has a three reservoir (plant interception, soil and groundwater) water balance model to estimate groundwater recharge. It uses rainfall and potential ET and a single variable that defines the maximum water balance storage as input data. WATBAL is used in the regional wheat yield forecasting model (STIN) of Stephens (1995).

2.1.1.2 GrowEst

GrowEst (Fitzpatrick and Nix 1970, Hutchinson *et al.* 2002) simulates potential pasture growth using a single layer soil profile assuming a single water holding capacity. It runs on a weekly or monthly time step. Due to its simplicity and computational efficiency, this type of model is still used in climate impact studies and agro-climatological classifications (Hutchinson *et al.* 2005). GROWEST and GROWEST PLUS (Brinkley *et al.* in press) have been improved and adapted over almost 40 years at different institutions.

2.1.1.3 PRIDE

The PRIDE model (Erlanger *et al.* 1992) estimates district water demands based on crop water requirement, taking into account knowledge of farmer practices and operating system constraints. It also takes crop cover and management into account in estimating on-farm requirements. Outputs from the PRIDE model can be integrated with the REALM system simulation model to account for capacity constraints outside the district and chances of seasonal allocations.

2.1.1.4 BiosEquil

A statistical steady-state landscape dynamics model, BiosEquil (Raupach *et al.* 2001a, Raupach *et al.* 2001b), uses a single water store. However, in an advanced and time-dependent version of this model (BiosEvolve), the water store is divided into two unsaturated soil pools corresponding to the stores in layers defined by the A and B soil horizons.

2.1.1.5 AWBM

The Australian Water Balance Model (AWBM) is a catchment-based water balance model that specifically calculates runoff at daily or hourly scales (Boughton 2004). The hourly-scale model is normally used for flood estimates whereas the daily-scale model is used to estimate water yield and water management studies. The single bucket model is employed in AWMB with varying surface water storage capacity (water holding capacity) to capture the effect of spatial variability.

2.1.2 Multiple layer simple models

O'Connell *et al.* (1970) developed a water balance model (SMAR) in the United Kingdom, in which water balance components operate in a manner analogous to a vertical stack of horizontal soil layers, in which they were able to incorporate the vertical heterogeneity of soil. Models in this category have been called multiple soil layer models. Most of the rainfall-runoff models based on catchment scale are simple water balance models with single or multiple soil layers.

While the assumption of uniform soils has been useful for spatial models, it does not especially hold over much of the Australian continent (Irannejad and Shao 1998), especially where duplex soils are common (NATMAP 1980). Irannejad and Shao (1998) improved simulation of soil moisture using a two-layered soil, and Greacen and Hignett (1976) developed a two-layer water balance model under wheat. Two layers are considered that broadly correspond to the surface and sub-soil horizons on which the growing root zone of the crop is imposed. Multiple-layer cascading water balance models developed in the last two decades owe much to their precursors in CERES (Jones and Kiniry 1986).

2.1.2.1 PERFECT

In line with the CERES model, PERFECT (Littleboy *et al.* 1992a) was developed as a cropping systems model to predict the effects of climate, soil type, crop sequence and fallow management on the water balance, erosion, crop growth and yield of cereal growing areas of the sub-tropics of Australia. This paddock scale model has multiple soil layers and is run on a daily time-step. The Williams-Ritchie (Ritchie 1972, Williams and La Seur 1976) water balance model used in PERFECT is also used in the CREAMS, EPIC and CERES models and has been extensively validated in the United States. Surface runoff is calculated as a function of rainfall, water balance deficit, surface roughness, surface residue and crop cover. Partial area runoff processes and subsurface flow are not considered. Water redistributed from the lowest profile layer is assumed to be lost as deep drainage. Transpiration is represented as a function of potential evaporation, leaf area and soil moisture. Soil evaporation is based on Ritchie's two stage evaporation algorithm (Ritchie 1972). Following infiltration, it is assumed that drying occurs at the potential rate until a user-defined limit is reached. When this limit is reached, the second and slower stage of soil evaporation commences.

2.1.2.2 SoilWat

The water balance component (SoilWat) of the APSIM modelling shell is the result of re-engineering of the CERES water balance and the introduction of alternative infiltration and runoff subroutines from PERFECT. Further enhancements for SoilWat have also occurred beyond CERES and PERFECT (Probert *et al.* 1998). Water movement is described using separate algorithms for saturated or unsaturated flows. Implementation of Richards’ equation in SWIM (which will be discussed in the next section of this paper) is the basis of an alternative water movement model in APSIM which includes solute transport algorithms (McCown *et al.* 1995).

2.1.2.3 GRASP

GRASP is a soil moisture/plant growth model simulating the hydrological processes of runoff, transpiration and soil evaporation (Rickert and McKeon 1982) and the biological processes of plant growth (McKeon *et al.* 1982). GRASP was developed with a combination of three empirical approaches in plant growth (Tupper *et al.* 2001). They are ‘growth index’ approach (Fitzpatrick and Nix 1970), ‘water use’ approach (Rose *et al.* 1972) and ‘radiation use efficiency’ approach (Charles-Edwards *et al.* 1986). This model has four-layer soil water budget. GRASP has been used in AussieGRASS as its plant growth and water balance module.

2.1.2.4 BASINMAN

Wu *et al.* (1999) developed the BASINMAN model with the aim of increasing the understanding of hydraulic relationships between farmed area and on-farm basins. BASINMAN is two-layered (saturated and unsaturated) simple bucket model. The drainage flow is calculated using Houghoudt drainage theory, and Darcy’s flow is adopted for interchange between basin and farm. Horizontal and vertical groundwater flows are calculated as fixed net inflow and fixed net down flow respectively. Crop water use is estimated with reference to ET and crop factors (FAO method).

2.1.2.5 CATSALT

The Catchment Scale Salt Balance Model (CATSALT) is a quasi-physical model developed to obtain salt balance at catchment scale (Tuteja *et al.* 2002). The water balance model of CATSALT is a rainfall-runoff based soil moisture accounting and routing model called SMAR (O’Connell *et al.* 1970, Kachroo 1992). The SMAR model divides the soil column into horizontal layers, which contain a prescribed amount of water at their field capacities.

Evaporation from soil layers is treated in a way that reduces the soil moisture storage in an exponential manner from potential ET. Simple empirical relationships have been employed to link ET with the land use. The routing component transforms the surface runoff generated from the water balance component to the catchment outlet by a gamma function model (Nash 1960) and also includes a groundwater runoff function as well. The effect of topography is introduced in CATSALT using a wetting index (Beven and Kirkby 1978) to disaggregate surface runoff within a given runoff.

2.1.2.6 Water flow assessment models

Models such as IQQM, REALM and MSM-BIGMOD have been developed for water flow and resource management. These models are also used to generate daily runoff volumes from catchments over a long period.

IQQM

Integrated quality and quantity model (IQQM) developed by the NSW Department of Land and Water Conservation (now the Department of Natural Resources) (Podger *et al.* 1984) is intended for use in investigating the impacts of water resource policies or policy changes on stakeholders. It is also used to investigate and resolve water sharing issues at the inter-state level. The water balance model component of IQQM is the Sacramento Soil Moisture Accounting (SAC-SMA) model, a conceptually based rainfall-runoff model with spatially lumped parameters (Burnash 1985, Burnash *et al.* 1973). The Antecedent Precipitation Index within SAC-SMA is one of the most common methods for simulating rainfall-runoff processes. Rainfall-runoff models are used to transform rainfall (rainfall on bare ground plus snow cover outflow) into runoff. SAC-SMA can explicitly account for soil moisture changes, while the API methods use indices to simulate the soil moisture conditions.

The SAC-SMA model represents the moisture distribution in a physically realistic manner within hypothetical zones of a soil column. The model attempts to maintain percolation characteristics to simulate streamflow contributions from a basin. The components of SAC-SMA are tension water, free water, surface flow, lateral drainage, ET and vertical drainage (percolation). The SAC-SMA model uses comprehensive runoff analysis in water balance accounting system.

REALM

The REsouce ALlocation Model (REALM) is a generalised simulation package for analysing the yield and security of water supplies and evaluating changes in operation of stream flows in Victorian river systems. It is able to simulate complex water management operating rules with a high degree of flexibility. In addition to rural water authorities in Victoria, REALM is also used by Melbourne Water. As stated earlier, REALM can use simple models, such as PRIDE, to estimate farm water requirements.

MSM-BIGMOD

The MSM-BIGMOD developed by the MDBC is relatively complex and includes rainfall-runoff relationships, operating rules for storages, irrigation demands, flow and salinity routing, water resource assessment and water accounting. It is a river systems model rather than a whole of catchment model and provides daily flows similar to IQQM's outputs.

2.2 Complex models

In complex water balance models, water movement is treated as continuous rather than a series of cascades as in the simple bucketing approach. Complex water balance models are based on fundamental equations for hydraulic and hydrodynamic behaviour and the movement of water and solute through porous media.

Richards' equation is the commonly accepted basis for detailed studies of vertical water movement (Ross 1990a). Analytical solutions to Richards' equation are not possible for dynamic field situations and therefore most models focus on numerical solutions (finite-difference or finite element methods) which have become practical with increased computing power. Broadbridge and White (1988) developed an analytical water balance model by solving Richards' equation to describe the relationships between water potential, volumetric water content and hydraulic conductivity. The Broadbridge and White (1988) water balance model is one of the earliest models developed in Australia using Richards' equation. It can realistically represent a comprehensive range of soil moisture characteristics (Zhang *et al.* 1996) and is subject to two levels of dimensionless scaling that lead to simple rules for guaranteed numerical performance (Short *et al.* 1995).

Darcy's law is not applicable for unsaturated conditions. However, Darcy's law can be, and has been, adapted for unsaturated flow by coupling it with the Richards' equation (Broadbridge and White 1988, Ranatunga and Murty 1992, Ross 1990b) assuming that hydraulic conductivity and diffusivity are functions of volumetric water content, not soil depth (Philips 1966). Hatton *et al.* (1992) and Vertessy *et al.* (1993) implicitly stated that the water balance of many Australian land systems does not have to be treated with a fully three-dimensional model, but rather may be approximated with a one-dimensional treatment (Zhang *et al.* 1996).

2.2.1 SWIM

Water balance Infiltration and Movement, SWIMv1 (Ross 1990b) also uses Richards' equation with an efficient numerical solution. It simulates infiltration, ET and redistribution. Version 2 of the model (identified as SWIMv2, Verberg *et al.* 1996) combines water movement with transient solute transport and accommodates a variety of soil property descriptions and more flexible boundary conditions. SWIM v2 also includes a numerical solution for the advection-dispersion equation. It can be used to simulate runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching. As stated earlier, prediction of crop growth and feedback has been addressed by incorporating SWIMv2 into the APSIM cropping systems framework (McCown *et al.* 1996).

2.2.2 Topog_Yield

The Topog_Yield model is a transient model of unsaturated-saturated flow and an application module in the Topog modelling framework (Beverly 1992, Vertessy *et al.* 1993). The Topog framework is composed of a 'kernel' and several catchment-based application modules. The kernel consists of a suite analysis of routines in which water balance computations are made. The Topog_Yield is designed to simulate slowly changing hydrologic states over long-term sequences, characterised by variable climatic conditions and landuse. It models unsaturated flow in the vertical direction and saturated flow in both the vertical and lateral dimensions. Vertical fluxes are handled using a fully implicit numerical solution of the Richards' equation, as was done by Ross (1990a, 1990b). If lateral subsurface flow occurs, it is routed downslope along the flow strips using Darcy's law.

In the TOPOG series, a spatially explicit hydroecological landscape model of water, carbon and energy balances has also been developed and named as Topog_IRM (Hatton *et al.* 1992, Dawes and Hatton 1993). It simulates the water balance and plant growth across three-dimensional catchments.

2.2.3 WAVES

WAVES (Dawes and Short 1993, Hatton *et al.* 1995) is a biophysical model which predicts the dynamic interactions within the soil-vegetation-atmosphere system. Although all the other models described above are similar in terms of the calculation of actual and/or potential ET, WAVES includes the physiological control of transpiration as a function of CO_2 assimilation rate, the vapour pressure deficit and the CO_2 concentration at the leaf surface. Similar to SWIM, WAVES also models soil hydrology using Richards' equation solved with the analytical solution given by Broadbridge and White (1988). Surface runoff was generated from the excess of precipitation intensity over soil infiltration rate and the occurrence of precipitation over saturated surfaces. As the non-zero topographic slope is specified as an input to the model, lateral surface flow that occurs via the saturated water table is described by Darcy's law.

2.2.4 ALSIS

A land surface parameterisation scheme (ALSIS) was developed with an emphasis on soil moisture prediction (Irannejad and Shao 1996, Irannejad and Shao 1998). ALSIS is essentially a surface hydrologic model for predicting ET, surface and subsurface runoff and deep drainage by parameterisation and solving the Richards' equation and the temperature diffusion equation for multi-soil layers. ALSIS accounts for the heterogeneity of soil hydraulic properties in the vertical direction. Parameters suggested by Broadbridge and White (1988) are used to characterise the heterogeneity of soil hydraulic properties in the vertical direction for various soils. A non-linear relationship between the root fraction and the soil depth is also employed in this model. Lyons *et al.* (1997) and Shao *et al.* (1997) used ALSIS to predict soil moisture over the Australian continent. Despite the capacity to handle vertical heterogeneity in ALSIS, Lyons *et al.* (1997) assumed the soil profile to be vertically homogeneous for continental analysis. Standard statistical evaluation, averaged over 30 sites in the Murray-Darling Basin, has shown that the model performance is very good. Irannejad *et al.* (1997) applied ALSIS to assess the impacts of vegetation cover on the water balance budget and found that increased vegetation cover increases total surface ET and decreases runoff and recharge.

2.2.5 CLASS

The Catchment scale multiple-Landuse Atmosphere Water balance and Solute transport model (CLASS) is a distributed, eco-hydrological modelling framework that deals with water and solute transport (Tuteja *et al.* 2004). The CLASS framework includes CLASS spatial analyst, unsaturated zone water balance model and pasture, tree and crop growth models. Since CLASS uses the Penman-Monteith equation to calculate ET, it can be used to investigate plant responses to temperature, radiation and water in a changing environment. CLASS uses Richards' equation for partitioning water balance in the unsaturated zone. After the local water balance is calculated for each grid cell on the land, excess moisture arising from the saturated conditions within each cell is then redistributed horizontally on the basis of multiple flow direction from the upslope contributing areas and Darcy's law. Total generated groundwater discharge from landscape to the stream is routed using a similar approach to the surface runoff. The sub-surface flow routing model is adopted from a grid-based quasi three-dimensional model of Wigmosta and Lettenmaier (1987). An important difference, as stated in Tuteja *et al.* (2004), between the approach of Wigmosta and Lettenmaier (1994) and the statistical dynamic approach called wetting index (used in CATSALT), is the use of grid cells instead of the use of hydrological similarity concepts. The numerically simple, hydrological similarity concept is not suitable for predicting the effects of landuse change.

2.2.6 SWAGSIM/SWAGMAN

CSIRO Land and Water developed a series of models designed to investigate shallow saline groundwater conditions. Models in this series include SWAGMAN (Meyer and Prathapar 1992), SWAGSIM (Prathapar *et al.* 1994, Prathapar *et al.* 1995, Prathapar *et al.* 1996), SWAGMAN Whatif (Robbins *et al.* 1995), SWAGMAN Destiny (Meyer *et al.* 1996), SWAGMAN Options (Prathapar *et al.* 1997) and SWAGMAN Farm (Khan *et al.* 2000). The objective of the groundwater modelling routine in this series is to determine the spatial response of the water table to recharge under rice fields. This is achieved by solving the forward finite difference approximation of the partial differential equation governing the non-steady state, two-dimensional flow of groundwater in an unconfined, non-homogeneous and isotropic aquifer (Prathapar *et al.* 1997), as outlined by Wang and Anderson (1982). SWAGMAN Farm and SWAGMAN Destiny are more widely used. SWAGMAN Farm is a lumped water balance model which predicts net recharge, changes in the depth to the water table and root zone salinity and other economic indicators of the farm. SWAGMAN Destiny is a more detailed crop model which can be used to determine crop productivity for a range of crops and pastures at a point in the landscape, in addition to outputs of net recharge and changes in water table and root zone salinity (Edraki *et al.* 2003). SWAGMAN model series can only simulate monocultures and its usefulness will be greatly improved by incorporating the ability to simulate crop sequences (Timsina and Humphreys 2003).

2.2.7 Models with soil-plant-atmosphere interactions

The relative capabilities of existing water balance models and the credibility of their results are still an important concern because water balance dynamics are generally inadequately represented in models of the soil-plant-atmosphere water interactions and processes (Clemente *et al.* 1994). However, incorporation of the soil-plant-atmosphere continuum requires much more input information that is unlikely to be satisfied given current data availability.

3. Data requirements

Catchment water balance models require a range of meteorological, soil, stream flow, irrigation and land use information. The availability of input data can prevent the application of catchment water balance models in particular regions. Brodie *et al.* (2004) provide a comprehensive review of water data in Australia. However, not all datasets relevant to water balance models are reviewed, including land use, vegetation, soils and irrigation data. Data availability is also discussed in manuals for some water balance models (e.g. Raupach *et al.* 2000a, Raupach *et al.* 2000b for BiosEquil and BiosEvolve).

3.1 Simple models

The single-layer simple models typically have modest data requirements. Many simple models require only limited meteorological and soil data. For example, WATBAL and GrowEst models need few input parameters. Most climate and soil input data for WATBAL and GrowEst are available both in point and spatial form across Australia. There are no climate data constraints for PRIDE as rainfall and pan evaporation data are readily available from both SILO PPD and the Bureau of Meteorology (see Chapter 4). Long-term monthly mean potential ET is also available to estimate actual ET. Channel capacity constraints required by PRIDE are specific to irrigation systems and are normally available from irrigation authorities (see Chapter 4). However, it would be difficult to obtain this data for the Australian continent.

The statistical steady-state model, BiosEquil, can be run with a fixed set of input data. All climatic data (long-term monthly means) are readily available. BiosEquil requires gridded meteorological, land use, land cover, irrigation, soil and nutrient data for the Australian continent (Raupach *et al.* 2001a; Raupach *et al.* 2001b). In terms of meteorological data, the model requires mean monthly and annual rainfall, solar radiation, temperature and humidity data.

BiosEvolve, the time-dependent version of the BiosEquil model, has the same input data requirements as BiosEquil except that BiosEvolve requires daily meteorological data rather than mean annual or monthly data (Raupach *et al.* 2001a; Raupach *et al.* 2001b). Gridded climate data for BiosEvolve are available from SILO PPD. Finding accurate information on soil properties such as hydraulic conductivity and water balance content at saturation for two soil layers could be difficult, though available from the ASRIS soil Geographical Information Systems (GIS) (see Chapter 4). Land cover and land use data are available from various sources.

AWBM has minimal data requirements (daily rainfall and actual ET). Daily rainfall is available from SILO PPD and daily ET can be estimated from pan evaporation, which is also available from SILO PPD. A time-series of daily stream flow is required for calibration. AWBM has been calibrated for 221 gauged catchments across Australia. The model can also be applied to ungauged catchments by selecting parameter values from nearby gauged (and calibrated) catchments with similar characteristics, such as rainfall, area and elevation (Boughton & Chiew 2003), although there may be instances were there are no nearby catchments with similar characteristics.

Daily rainfall and monthly evaporation data have been used in the AWBM to estimate daily runoff. The AWBM also requires specific coefficients for runoff characteristics and base flows (baseflow index and baseflow recession constant). A self-calibrating version of the model for these constants has performed well for most catchments (Boughton 2004).

In contrast to single-layer models, multiple layer models often require soil and water characteristics for each soil layer. Multiple layer models treat soil evaporation more realistically, but also demand additional information. As with PRIDE, there are no climate data constraints for PERFECT. Gathering site-specific soil properties such as soil thickness, bulk density and water balance characteristics is not easy. However, soil parameters can be measured or estimated using surrogate techniques. The ASRIS soil GIS and other soil datasets can provide such soil properties for the continent.

Data constraints described in PERFECT, such as irrigation and soil data, often apply for SoilWat as well. The advantage of having empirically-developed relationships in GRASP is that the model requires relatively few parameters to calibrate. As with PRIDE, all the data constraints associated with the FAO method to estimate ET and most of the constraints in relation to soil properties and hydrology (discussed in PERFECT and SoilWat) are applicable for BASINMAN.

The CATSALT model requires a range of meteorological, soil, land use, stream flow, groundwater and salinity datasets (Tuteja *et al.* 2003; Tuteja *et al.* 2004). Daily rainfall and pan evaporation are the only meteorological data required by CATSALT, although a pan evaporation factor is required to convert pan evaporation to potential ET.

As a distributed model, CATSALT requires spatial input datasets including land use, soil landscape and depth to groundwater. Additional soil data is also required including soil type, thickness of horizons, water balance content at field capacity and water balance holding capacity. CATSALT is also reliant on inputs from other models, including the TOPMODEL Wetness Index and HYDRUS-2D.

As a water and salt balance model, CATSALT also requires a number of salinity data sets: stream salinity, rainfall salinity, groundwater salinity, salinity in the soil profile and salinity hazard mapping. In addition, three parameters (α, K_F and β) are required to describe salt behaviour in the soil profile and baseflow. Daily stream flow data is required for model calibration.

Spatial climate data required by CATSALT are available from the Bureau of Meteorology (BoM) as well as SILO PPD. Soil and hydrological characteristics are also available from (not-so-accurate) ASRIS soil GIS. Stream flow data required for CATSALT are generally available from state and territory agencies and spatial coverage of landuse is available from a range of sources.

Spatial estimates of long-term mean monthly and annual ET required by IQQM/SAC-SMA can be accessed though the BoM. SILO PPD produces daily and monthly spatial estimates of pan evaporation across the continent, which can be used to calculate daily ET in IQQM/SAC-SMA. This model also requires numerous data relating to runoff, groundwater and percolation, which are not readily available. Similar to CATSALT, stream flow data required for SAC-SMA are generally available from state and territory agencies. In terms of data constraints, REALM and MSM-BIGMOD also have concerns similar to IQQM and SAC-SMA.

AussieGRASS (GRASP) requires spatial meteorological, soils, vegetation and stock management data. Daily grids of rainfall, minimum and maximum temperature, pan evaporation, solar radiation and vapour pressure deficit are required (Carter *et al.* 2000). Soil type and parameters are required for four soil layers including layer thickness, bulk density and water soil content (at air dry state, wilting point and field capacity). The upper limit to daily soil evaporation must also be specified.

AussieGRASS has eight pasture parameters including transpiration efficiency and potential growth rate per unit of grass basal cover. These data are obtained through calibration against pasture biomass measured in the field. Management information, such as stocking rates, is also incorporated into the model.

The data requirements for both single layer and multiple layer simple models are summarised in Table 1.

3.2 Complex models

The data requirements of the complex models reflect their original purpose. Water and salt balance models, such as APSIM and SWAGMAN, have much greater requirements for soil and solute data. Models designed to study the impact of crops and other vegetation on the water balance require more information about agronomy.

SWIM requires climate, soil, runoff, surface storage and vegetation data (Kumar and Purandara 2003). Daily rainfall and potential evaporation are the only required meteorological data. Soil data includes characteristics of the soil water retention and soil hydraulic conductivity curve and hydraulic conductivity and soil water content at wilting point and at saturation. In addition to climate data required in SWIM, APSIM-SWIM (APSWIM) requires rainfall duration or intensity, which is not readily available for most areas. However, APSWIM has substantially changed its soil parameterisation, which contributes to a present lack of clarity of the cost-effectiveness of the two approaches in SoilWat and APSWIM (Williams *et al.* 1991). Most of the soil and hydrological information required for SWIM and APSIM are site-specific.

WAVES can run either with minimal climate datasets (rainfall and temperature) or additional climate datasets (vapour pressure deficit, solar radiation and rainfall duration). WAVES requires details of soil structure which are not easy to obtain. WAVES also requires management information. Both SWAGSIM and SWAGMAN require all the standard climate data except evaporation. SWAGMAN requires more soil hydrological and cropping data, but less hydrogeological data than SWAGSIM. SWAGMAN Farm and Destiny models have been evaluated extensively by Edraki *et al.* (2003) and highlight the importance of good knowledge of the regional hydrology in terms of deep and lateral flows for rational applications of these models.

Spatially-based complex soil water models require spatial information on soil and soil hydrology. As stated earlier, this information is available from the ASRIS soil GIS. Land cover and land use data are also available from various sources. ALSIS requires considerable soil and water characteristics spatially in its current form, but for initial simulations, it assumes a vertically homogeneous soil for continental analysis.

Topog_Yield is based on an ‘element network’ generated from a high resolution topographic contour map or digital elevation model (DEM). Climate, soil and vegetation data are needed to parametise the element network (Vertessy *et al.* 1993). Topog_Yield requires a time series of daily climate data including total rainfall, maximum temperature, minimum temperature, mean vapour pressure deficit, and total direct and diffuse solar radiation. Soil data are also required by the model including depth, saturated hydraulic conductivity, water balance content (at saturation and air dry), soil structure parameter and capillary length scale for all soil layers.

Topog_Yield also has nine vegetation parameters: leaf area index, rainfall interception coefficient, canopy albedo, light extinction coefficient, maximum leaf water potential, maximum canopy conductance, aerodynamic resistance and slope of canopy conductance-vapour pressure deficit curve.

As a spatially distributed model, CLASS requires spatial input data to characterise the climate, elevation, land use, hydrogeology and soils in the study region. Temporal data are required to calibrate and validate the model (Tuteja *et al.* 2004). Considerable amounts of information are required to fully utilise and parametise the suite of CLASS models.

In terms of climate data, CLASS requires gridded daily rainfall, maximum and minimum temperature, pan evaporation, maximum and minimum relative humidity, shortwave radiation and vapour pressure.

CLASS requires a number of spatial datasets to describe topography and hydrology including a digital elevation model (DEM), the Fuzzy Landscape Analysis Geographic information system (FLAG) Upness Index and the Multi-Resolution Valley Bottom Flatness (MRVBF) Index. The FLAG Upness Index delineates areas of surface and subsurface water accumulation. The MRVBF Index distinguishes lowland, depositional landscapes from upland, erosional landscapes, and can be used to predict soil depth and soil moisture storage capacity. Other spatial datasets required by CLASS include land use, soil type, soil salinity and groundwater flow systems accompanied by metadata on solute concentration, hydraulic conductivity, transmissivity, specific yield and depth for all aquifers.

CLASS also requires time series data (in-stream or terrestrial) for calibration and validation. The minimum requirements for calibration are time series stream flow and solute concentration at the catchment outlet. Additional data for gauging stations within the catchment can also be used in calibration and validation. Terrestrial datasets relating to hydrology and plant growth can be used for validation including soil moisture, Leaf Area Index (LAI), stem and root biomass and groundcover. Additional information is required for each of the component models: CLASS U3M-1D, U3M-2D, Catchment Model, PGM, CGM and 3PG+ (refer to Teng *et al.* 2004; Vaze *et al.* 2004a; Vaze *et al.* 2004b; Vaze *et al.* 2004c). The component plant growth models require considerable amounts of information for parametisation. For example, the crop model has around eight soil physical/hydraulic properties and around 30 parameters relating to crop growth, management, salt tolerance and root depth.

CLASS has made considerable attempts to resolve data constraints often imposed in catchment scale management. In addition to other climate data described in Topog_Yield, CLASS requires evaporation data, which can be sourced from the SILO PPD. Unlike the other models in this category, soil type is the only soil and hydrological property required by the model. However, it needs considerable amounts of information about hydrogeology, for example, groundwater flow systems and water table mapping. CLASS also requires leaf area index and several indices related to remote sensing, as well as land use coverage which is available from various sources (as discussed in BiosEquil and CATSALT). The CLASS model is designed for Australian conditions and data constraints often imposed in catchment scale investigations have been taken care of in designing various components of the model. In particular the model is adapted to spatial data and tools relating to soils, topography and groundwater flow systems commonly used in Australia.

The data requirements for complex soil water models are summarised in Table 2.

Table 1 Input data requirements for simple soil water models

Input Data	WATBAL	GROWEST	PRIDE	BiosEquil	AWBM	PERFECT	APSIM SoilWat	SAC-SMA (in IQQM)	BASINMAN	CATSALT	BiosEvolve	GRASP
Climate												
Rainfall	√	√	√	√	√	√	√	√	√	√	√	√
Temperature		√		√		√	√				√	√
Pan Evaporation/Evapotranspiration	√	√	√		√	√	√	√	√	√		√
Solar radiation		√		√		√	√				√	√
Humidity/vapour pressure deficit				√							√	√
Additional climate variables									√			√
Soil												
Soil type				√		√	√			√	√	√
Soil depth				√		√	√			√	√	
Soil texture		√		√							√	
Additional physical soil properties						√	√					
Soil hydrology												
Soil water holding capacity	√	√								√		
Initial soil water content	√					√	√		√	√		
Soil water content at air dry state						√	√					
Soil water content at field capacity						√			√			
Soil water content at wilting point						√			√			

Table 1 (cont')

Input Data	WATBAL	GROWEST	PRIDE	BiosEquil	AWBM	PERFECT	APSIM SoilWat	SAC-SMA (in IQQM)	BASINMAN	CATSALT	BiosEvolve	GRASP
Soil water content at saturation				√		√	√		√	√	√	
Upper limit of water content							√					√
Lower limit of water content							√					√
Hydraulic conductivity				√		√	√		√		√	
Additional soil hydraulic properties						√	√	√	√			
Hydrogeology												
Aquifer/aquitard thickness									√			
Additional hydrogeological parameters								√				
Stream flow												
Stream flow					√			√		√		
Additional stream flow parameters					√			√				
Land use and vegetation												
Land use				√						√	√	√
Land cover				√							√	√
Leaf Area Index (LAI)						√						
Agronomy												
Crop type			√			√						

Table 1 (cont')

Input Data	WATBAL	GROWEST	PRIDE	BiosEquil	AWBM	PERFECT	APSIM SoilWat	SAC-SMA (in IQQM)	BASINMAN	CATSALT	BiosEvolve	GRASP
Cropping sequence/dates						√						
Crop management e.g. fallow, herbicide						√						
Additional crop parameters			√			√			√			
Irrigation												
Irrigated area / amount			√	√							√	
Irrigation infrastructure/capacity			√						√			
Irrigation management									√			
Salinity												
Rainfall										√		
Soil										√		
Groundwater												
Runoff – Curve number							√			√		
Salinity hazard mapping										√		
Other												
Solute/nutrients concentration				√							√	√

Table 2 Input data requirements for complex soil water models

Input data		SWIM	APSIM SWIM	WAVES	ALSIS	CLASS	SWAGSIM	SWAGMAN	TOPOG_Yield
Climate									
	Rainfall	√	√	√	√	√	√	√	√
	Temperature			√	√	√	√	√	√
	Evaporation	√	√			√			
	Solar radiation			√		√	√	√	√
	Humidity/VPD/dew point		√	√		√	√	√	√
Soil									
	Type	√	√	√	√	√	√	√	√
	Depth	√	√	√			√	√	√
	Texture			√					
	Structure			√					√
	Bulk density	√	√						
	Root zone depth						√	√	
	Soil water holding capacity				√				
	Initial soil water content	√	√	√	√		√	√	
	Hydraulic conductivity	√	√				√	√	√
	Soil water at air dry state								√

Table 2 (cont')

Input data		SWIM	APSIM SWIM	WAVES	ALSIS	CLASS	SWAGSIM	SWAGMAN	TOPOG_Yield
	Soil water at wilting point							√	
	Soil water at field capacity							√	
	Soil water at saturation						√	√	√
	Soil metric potential	√	√	√			√	√	√
Hydrology / Hydrogeology									
	Stream flow	√							
	Aquifer depth/thickness					√	√	√	
	Water table						√	√	
	Groundwater Flow Systems					√			
	Hydraulic conductivity					√	√	√	
	Transmissivity					√	√		
	Specific yield					√	√		
	Groundwater extraction						√	√	
Landuse and vegetation									
	Land use					√	√		
	Land cover								
	Vegetation type	√			√				√

Table 2 (cont')

Input data		SWIM	APSIM SWIM	WAVES	ALSIS	CLASS	SWAGSIM	SWAGMAN	TOPOG_Yield
	Vegetation height				√				
	Leaf Area Index (LAI)				√				√
Agronomy									
	Crop types						√	√	
	Crop factor							√	
	Management	√	√	√				√	
Irrigation									
	Irrigation applications		√				√	√	
	Irrigated area						√	√	
	Infrastructure		√				√		
Salinity									
	Rainfall							√	
	Soil					√		√	
	Groundwater					√		√	
	Runoff							√	
	Stream					√			
	Irrigation water							√	

Table 2 (cont')

Input data		SWIM	APSIM SWIM	WAVES	ALSIS	CLASS	SWAGSIM	SWAGMAN	TOPOG_Yield
	Economic component							√	
	Digital Elevation Model					√			√
	Nutrient/solute concentration	√	√						

4. Data availability

4.1 Meteorological data

The two main sources of meteorological data in Australia are BoM and the Queensland Department of Natural Resources and Mines' (QDNRM) SILO Patched-Point Dataset (SILO PPD). BoM maintains a network of several thousand weather stations throughout Australia (Figure 3). All weather stations monitor rainfall on a daily basis; some weather stations also monitor other climate variables, such as minimum and maximum temperature, solar radiation, pan evaporation and humidity (Table 3). The historical record for climate variables varies depending on the station and the variable, but some stations extend back to 1980 for rainfall. Many stations do not have a continuous record, which can cause significant problems for water balance modelling.

The SILO PPD is an attempt to overcome some of the problems associated with data from BoM's weather stations. Missing records have been infilled using spatial interpolation to provide continuous daily records of climate variables, such as rainfall, minimum and maximum temperature, solar radiation, vapour pressure and pan evaporation (Jeffrey *et al.* 2001). Data is available for 4600 sites across Australia (Figure 4). Both agencies also produce grids of climate data for the Australian continent. These spatial datasets will be the focus of the following review.

4.1.1 Rainfall

Rainfall is a required input for all water balance models. As the largest term in the water balance, rainfall is a significant source of error in water balance modelling (Boughton 2005; Murray *et al.* 2005). Rainfall data is particularly problematic when using lumped rainfall models in areas where there is high spatial variability in rainfall, and the rainfall input (i.e. from a single weather station) is not representative of the area as a whole. The distribution and density of rainfall stations is recognised as a source of error in spatial rainfall datasets. Boughton (2005) states that the standard rain gauge has a collection area of 1/3,000,000 km^2 compared to a rain gauge density in Australia of one gauge to 10-100 km^2. Monitoring stations are scarce in some regions, particularly areas of central Australia and the rangelands of Queensland. There are also errors associated with spatial interpolation. However, the BoM is implementing improved techniques using topography as an independent variable to reduce the error in their spatial datasets (after Hutchinson *et al.* 1998a, Hutchinson *et al.* 1998b).

BoM produces daily and monthly rainfall grids at 0.25 degree (~25 km) resolution for the Australian continent (Table 4). The historical record for this dataset extends back to 1980. The grids are designed for broad scale analysis and may not be appropriate for some water balance models, particularly the point and farm scale models.

In addition, BoM is currently developing rainfall grids at a finer spatial resolution using enhanced interpolation techniques (Jones *et al.* 2004). The grids are being developed as part of the Natural Heritage Trust-funded Australian Water Availability Project and will become available to the public in 2008. When completed, daily and monthly rainfall grids will be available at a 0.05 degree (~5 km) resolution with a historical record will extending back to 1900 (Table 4).

As part of the SILO PPD, daily and monthly rainfall grids are available as 0.05 degree (~5 km resolution) from 1980 to present (Table 4). The grids are based on data from BoM's weather stations using ordinary kriging for spatial interpolation (Jeffrey *et al.* 2001).

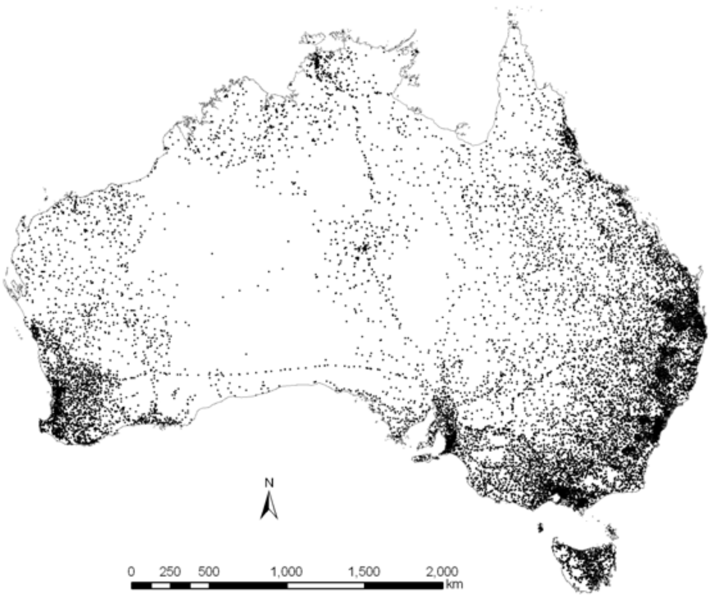

Figure 3: Location of BoM's weather stations

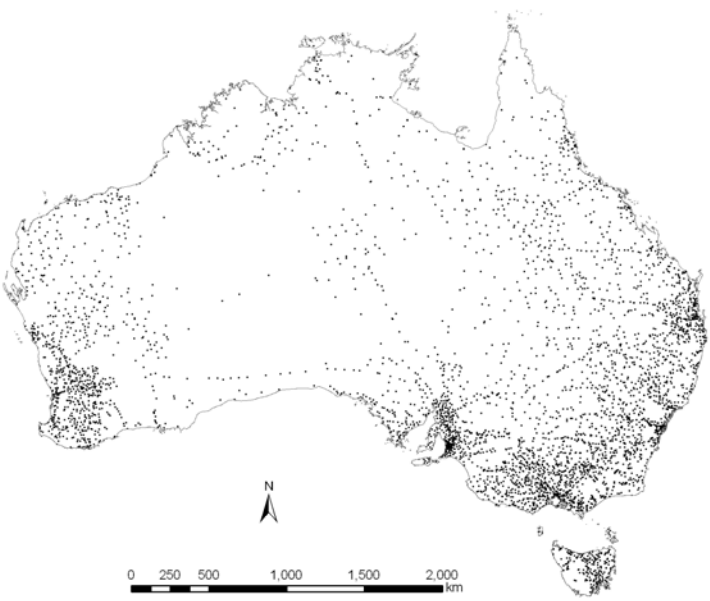

Figure 4: Location of SILO PPD sites (after Jeffrey et al. 2001)

Table 3: Selected climate variables available from BoM and QDNRM's SILO PPD (BoM 2005; Jeffrey *et al.* 2001)

	Number of sites	
Variable	**Bureau of Meteorology**	**SILO PPD**
Dew point (humidity)	1533	-
Pan evaporation	585	4600
Rainfall	17,665	4600
Solar radiation	86	-
Temperature (min & max)	1917	4600
Wind speed	1917	-

Table 4: Characteristics of spatial rainfall datasets for the Australian continent

	Bureau of Meteorology	**NHT-funded AWAP**	**SILO PPD**
Custodian	Bureau of Meteorology	Bureau of Meteorology	Queensland Department of Natural Resources and Mines
Spatial resolution	0.25 degrees	0.05 degrees	0.05 degrees
Spatial extent	Australia	Australia	Australia
Temporal resolution	Daily and monthly	Daily and monthly	Daily and monthly
Historical record	~1900-present	~1900-present	~1900-present
Spatial interpolation	Barnes analysis	3-D smoothing spline (climatology) + Barnes analysis (anomaly field)	Ordinary kriging
Access	By request	Available on-line in 2008	License required

4.1.2 Evaporation and ET

ET is typically the second largest term in the water balance. Although the spatial and temporal variability of ET is not as large as for rainfall, ET is still a significant source of error in water balance modelling. It is difficult to quantify the errors associated with ET because there are few observed datasets to validate modelled actual ET. The observations are generally made in small scale studies, and may not be appropriate for validation of broad scale estimates. The most comprehensive databases of observed ET have been compiled by Humphreys *et al.* 2003 and Zhang *et al.* 1999b.

Two broad types of ET data are required by water balance models: potential ET and actual ET. Both types can be calculated (or measured) using a range of techniques; there is no universally accepted method for calculating either variable. A detailed discussion of the common methods used in Australia is given in Chiew *et al.* 1995. Some of the methods commonly used for estimating ET include:

- Class-A pan evaporation (and a pan coefficient);
- Penman-Monteith equation;
- Priestly-Taylor equation;

- Morton's equation; and
- FAO-24 reference crop ET (and crop coefficients).

The available ET products have been created using a range of these techniques. The different methods for calculating ET can produce significantly different estimates. For example, Chiew *et al.* 1995 compared a range of methods for calculating ET at 16 sites across Australia, and found that the FAO-24 estimates were generally 20-40% higher than the Penman-Monteith estimates.

Spatial estimates of mean monthly and annual ET are available from BoM (Table 5). Areal actual, areal potential and point potential ET are available as grids at a 0.1 degree (~10km) resolution. The estimates are derived using Morton's equation (Wang *et al.* 2001). The positional accuracy of the datasets is estimated to be 0.05 degrees (~5km), while the attribute accuracy ranges from 5 to 15%.

Grids of mean monthly and annual pan evaporation are available from BoM. Pan evaporation is also part of the QDNRM's SILO PPD. Daily pan evaporation is available as grids at a 0.05 degree resolution and individually for 4600 weather stations (Table 5).

Broad-scale spatial estimates of ET are available from CSIRO. Mean monthly and annual ET (potential and actual) have been calculated by Raupach *et al.* (2001a, 2001b) using the BiosEquil model (Table 5). The 5km by 5km grids are available from the CSIRO by request.

Table 5: Characteristics of spatial evaporation and ET datasets for the Australian continent

	Potential and actual evapotranspiration	**Class-A pan evaporation**	**Potential and actual evapotranspiration**	**Class-A pan evaporation**
Custodian	Bureau of Meteorology	Bureau of Meteorology	CSIRO	Queensland Department of Natural Resources and Mines
Spatial resolution	0.25 degrees	0.25 degrees	0.05 degrees	0.05 degrees
Spatial extent	Australia	Australia	Australia	Australia
Temporal resolution	Mean monthly and annual	Mean monthly and annual	Mean monthly and annual	Daily and monthly
Historical record	NA	NA	NA	1970-present
Method	Morton's equation	NA	Priestly-Taylor	NA
References	Wang *et al.* 2001	BoM 2005	Raupach *et al.* 2001a, Raupach *et al.* 2001b	Jeffrey *et al.* 2001

4.1.3 Temperature

Minimum and maximum daily temperatures are common inputs to water balance models that calculate ET, such as BiosEquil and PERFECT. Spatial temperature data can be sourced from the BoM and QDNRM's SILO PPD (Table 6). Daily and monthly grids of minimum and maximum temperature are available from BoM at a 0.25 degree (`25 km) resolution with a historical record extending back to 1950. Improved daily temperature grids with a 0.05 degree (~5 km) resolution will become available in 2008 through the Natural Heritage Trust-funded

Australian Water Availability Project (Jones *et al.* 2004). Daily and monthly temperature grids from 1957 to present are also available at a 0.05 degree resolution from the SILO PPD (Jeffrey *et al.* 2001).

Table 6: Characteristics of spatial temperature (minimum and maximum) datasets for the Australian continent

	Bureau of Meteorology	**NHT-funded AWAP**	**SILO PPD**
Custodian	Bureau of Meteorology	Bureau of Meteorology	Queensland Department of Natural Resources and Mines
Spatial resolution	0.25 degrees	0.05 degrees	0.05 degrees
Spatial extent	Australia	Australia	Australia
Temporal resolution	Daily and monthly	Daily and monthly	Daily and monthly
Historical record	1950-present	1910-present	1957-present
Method	Barnes analysis	3-D smoothing spline (climatology) + Barnes analysis (anomaly field)	Thin plate smoothing spline
Access	By request	Available on-line in 2008	License required

4.1.4 Other meteorological data

Some water balance models require other meteorological inputs, particularly to calculate ET, including:

- solar radiation;
- dew point temperature
- relative humidity;
- vapour pressure;
- vapour pressure deficit;
- wind speed; and
- soil albedo.

These variables are measured at selected weather stations, and point-based data can be sourced from BoM. Temperature, solar radiation and vapour pressure are available from QDNRM's SILO PPD.

Not all of these climate variables are available as spatial datasets (Table 7). Of these climate variables, only solar radiation (mean monthly and annual) is currently available from BoM as a spatial dataset. Additional spatial datasets will become available through the Australian Water Availability Project including solar radiation, vapour pressure and wind speed. These datasets will be available as daily grids at a 0.05 degree (~5km) resolution for solar radiation and vapour pressure, and a 2.5 degree (~250km) resolution for wind speed. The historical record will be from 1980 to present for vapour pressure, wind speed and solar radiation (Jones *et al.* 2004).

Daily grids of relative humidity, solar radiation, vapour pressure and vapour pressure deficit are available at a 0.05 degree (~5 km) resolution from the SILO PPD. The historical record for these data extends back to 1957 (Jeffrey *et al.* 2001).

Table 7: Summary of spatial climate datasets for the Australian continent

Variable	Bureau of Meteorology	Australian Water Availability Project	SILO Patched Point Dataset	CSIRO Land and Water
Rainfall	x	x	x	
Pan evaporation	x	x	x	
Potential ET	x			x
Temperature (min & max)	x	x	x	
Solar radiation	x	x	x	
Relative humidity	x		x	
Wind		x		
Vapour pressure		x	x	
Dew point				
Vapour pressure deficit			x	
Rainfall duration				
Soil albedo				

4.2 Soil and soil hydraulic properties

Soil data, and particularly soil hydraulic properties, are an important input to water balance models. Broad-scale soil data is available from three national datasets: the Digital Atlas of Australian Soils, the Australian Soils Resource Information System and the Cooperative Research Centre (CRC) for Catchment Hydrology’s Soil Hydrological Properties of Australia. The soil properties available in these datasets are summarised in Table 8.

The Digital Atlas of Australian Soils comprises a national soil landscapes map at a 1:2 million scale and associated soil properties (Northcote *et al.* 1960-68). The dominant soil type is provided for each soil landscape, although it is noted that soil landscapes may comprise many soil types. A range of soil properties is given for each soil type including permeability, water holding capacity, texture, reaction trend, nutrient response and depth.

The Australian Soils Resource Information System (ASRIS) is a more recent soils database, but is limited to Australia’s intensive agricultural zone (Figure 5) (Johnston *et al.* 2003). The database comprises soil profiles, soil maps, modelled surfaces of soil properties and a range of other datasets, such as climate, land use and a digital elevation model (DEM). The methods used to model the surfaces of soil properties are described in McKenzie *et al.* 2000 and Johnston *et al.* 2003. Spatial datasets are available at a 0.01 degree (~1 km) resolution for an upper and lower soil layer. Clay content, silt content, sand content, texture, thickness, bulk density, erodibility, water holding capacity, saturated hydraulic conductivity, pH and organic carbon are available for both soil layers, whereas total and extractable phosphorus and nitrogen are available for the upper layer only. ASRIS also contains over 160,000 soil profiles and associated soil properties. A greater range of soil properties are available for the soil profiles than are available as continuous grids. The range of soil properties includes the concentration of numerous elements, cation exchange capacity and unsaturated hydraulic conductivity (Johnston *et al.* 2003).

Table 8: Soil properties available from broad-scale spatial datasets

	Digital Atlas of Australian Soils	**Australian Soils Resource Information System**	**Soil Hydrological Properties of Australia**
Depth	x		x
Thickness		x	x
Texture	x	x	
Bulk density		x	
Erodibility		x	
Permeability	x		
Water holding capacity	x	x	x
Saturated hydraulic conductivity		x	x
Water balance at field capacity			x
Water balance at wilting point			x
Other	nutrient response, reaction trend	pH, carbon, phosphorus, nitrogen, clay, silt, sand	porosity
Reference	Northcote *et al.* 1960-19668	Johnston *et al.* 2003	Western & McKenzie 2004

The CRC for Catchment Hydrology's Soil Hydrological Properties of Australia was designed specifically as an input to water models (Western and McKenzie 2004). It is derived from the Digital Atlas of Australian Soils (Northcote *et al.* 1960-68) and the techniques used to create the ASRIS datasets (McKenzie *et al.* 2000). The dataset comprises 0.01 degree (~1 km) grids of soil properties for upper and lower soil layers for the Australian continent. The available soil properties include depth, plant available water holding capacity, saturated hydraulic conductivity, porosity and water balance content (at field capacity and wilting point).

State and Territory government agencies also maintain soils databases. Most soil databases contain a combination of soil mapping and point-based measurements of soil properties. For example, the New South Wales Department of Infrastructure, Natural Resources and Planning (DPINR) maintain a Soil and Land Information System (SALIS) for New South Wales. SALIS consists of 55,500 point based measurements of soil properties from across the state, and a series of hard copy soil landscape maps (McGaw *et al.* 2001).

In addition, soil properties for reference soil types can be found in the literature (e.g. Geeves *et al.* 1995, McKenzie *et al.* 2004, Stace *et al.* 1968) For example, standard water balance curves are available for major soil textures (i.e. clay, sand, sandy loam).

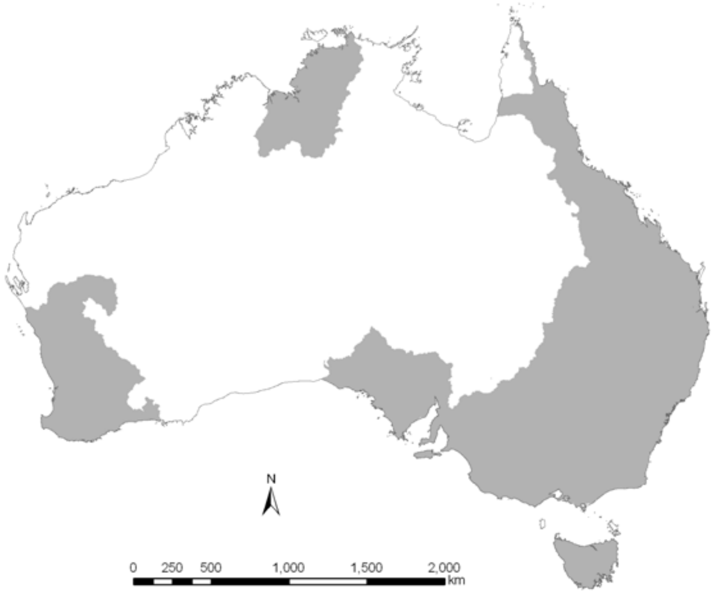

Figure 5: The extent of the ASRIS database i.e. intensive agricultural zone (after Johnston *et al.* 2003)

4.3 Stream flow

Stream flow data are often required by water balance models, such as CLASS and CATSALT, for validation and calibration. Stream flow gauges are managed by state and territory agencies, and data is available from these agencies by request or on the web (Table 9). Daily and monthly data from more than 500 gauging stations across Australia have been assembled from the state and territory agencies by the Queensland Department of Primary Industries as part of the RAINMAN project (Clarkson *et al.* 2001). This stream flow data is only available for streams without major dams or diversions and where consumptive use accounts for less than 5% of mean annual stream flow. The historical record for many of the gauging stations is less than 30 years.

In addition to the stream gauges managed by state and territory agencies, BoM maintains a network of more than 1900 stream gauges across Australia for flood monitoring. BoM also maintains a database of stream gauges across Australia including gauges managed by BoM, state and territory agencies and private companies. The database provides information about the location, historical record, maximum water level and missing records, but it does not provide access to the stream flow data.

Mean annual stream flow data have been compiled for the 245 Australian River Basins by the Australian Water Resources Commission (AWRC 1987) and the National Land and Water Resources Audit (NLWRA 2000). However, it is important to note that these datasets are not stream flow measurements from a gauge at the river basin outlet. A wide range of techniques, such as modelling and area-weighted interpolation of observations, have been used to generate the data. Despite the limitations of these datasets, they have been used to validate water balance models in the past (e.g. BiosEquil– Raupach *et al.* 2001a, Raupach *et al.* 2001b).

A high quality dataset of monthly stream flow from 1901-1988 was assembled by Peel *et al.* (2000) for 286 stream flow gauges mainly in eastern Australia (Figure 6). Unfortunately the catchments are relatively small with areas between 50 km^2 and 2000 km^2, and are not representative of the entire continent.

Table 9: Stream flow databases in Australia (after Brodie *et al.* 2004)

Database	State	Agency	Gauges	Access
-	ACT	Environment ACT	68	By request: http://www.tams.act.gov.au/live/environment
NSW Water Information	NSW	Department of Infrastructure, Planning and Natural Resources	1,700	Online: http://waterinfo.nsw.gov.au/
-	NT	Department of Infrastructure, Planning and Environment	160	By request: http://www.ipe.nt.gov.au/
WaterShed	QLD	Department of Natural Resources and Mines	5,000	Online: http://www.nrm.qld.gov.au/watershed/index.html
Surface Water Quantity (Levels and Flows)	SA	Department of Water, Land and Biodiversity Conservation	1,035	By request: Walker.CraigM@saugov.sa.gov.au
Water Information System of Tasmania	TAS	Department of Primary Industries, Water and Environment	-	Online: http://water.dpiw.tas.gov.au/wist/ui
Water Data Warehouse	VIC	Department of Sustainability and Environment	80,000	Online: http://www.vicwaterdata.net/vicwaterdata/home.aspx
Water Resource Information Catalogue	WA	Department of Water	111,280*	By request: http://203.20.251.100/waterinformation/wric/DataRequestPage.asp

*WIN includes surface water, groundwater and meteorological sites

There are many problems associated with the quality of stream flow data, which have implications for model calibration and validation. Firstly, there are errors associated with measurement of stream flow, particularly during storm events. Stream flow record can often be incomplete for the same reason. Stream flow datasets often have a much shorter historical record than climate datasets, which can be problematic for model validation and calibration. Moreover, stream gauges may not be situated in the desired location, typically the catchment outlet. Therefore it may be necessary to use the closest stream gauge and to use techniques, such as area-weighted interpolation, to extend the stream flow data to the catchment outlet.

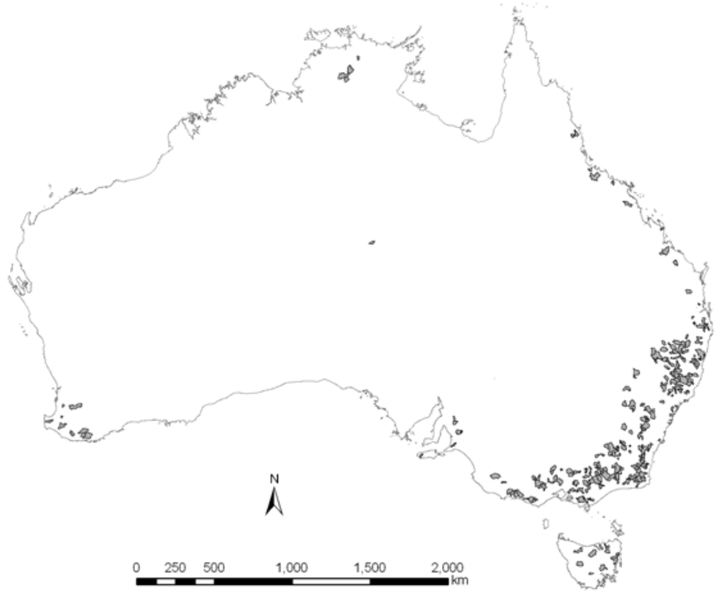

Figure 6: The catchment boundaries for the stream flow gauges used in Peel *et al.* 2000

4.4 Land use and vegetation

Land use and vegetation mapping is required by a number of distributed water balance models, such as BiosEquil, BiosEvolve and CLASS. Continental-scale land use and vegetation maps are either produced by or collated by BRS from data collected by state and territory agencies. These datasets are summarised in Table 10.

National-scale land use maps are produced by BRS. They provide complete coverage of the Australian continent at a 1: 2.5 million resolution. A combination of satellite imagery and Australian Bureau of Statistics (ABS) agricultural commodity data have been used to create maps of land use for the years 1983, 1985, 1987, 1986, 2000 and 2002 (Stewart *et al.* 2001). Land use is divided into a range of agricultural and non-agricultural uses using the Australian Land Use and Management (ALUM) classification. Only the dominant land use for the year is represented on the maps and hence, crop rotations are not represented (Stewart *et al.* 2001).

Catchment-scale land use mapping is compiled by BRS, but it is not yet available for the entire continent (Lesslie *et al.* 2003). It is currently available for all South Australia, Western Australia, Queensland, Northern Territory and Tasmania, most of Victoria and some of New South Wales; it is not available for the ACT. The spatial resolution depends on the nature of land use in the region: 1:25,000 for urban areas; 1:50,000 for coastal areas; 1:100,000 for areas of intensive agriculture; and 1:250,000 for all other areas.

Land cover mapping is available from BRS and the CRC for Catchment Hydrology. BRS' gridded land cover data is available for 1980 and 1985 at 25m, 100m and 250m resolutions. The CRC for Catchment Hydrology's 'Land Cover for the Intensive Use Zone of Australia' is derived from BRS's land cover dataset, and is available at a 1km resolution (Western 2005).

National-scale vegetation mapping is compiled by BRS and the Australian Government Department of Environment and water resources (DEW). The available vegetation datasets include:

- Integrated Vegetation Cover 2003
- Forests of Australia 2003
- National Vegetation Information System (NVIS)
- National Plantation Inventory (NPI)

The Integrated Vegetation Cover is the most comprehensive dataset as it is compiled from the other vegetation datasets, and provides complete coverage of Australia (Thackway *et al.* 2004).

Leaf Area Index (LAI) is used by a number of water balance models for parametisation (e.g. BiosEquil) and validation (e.g. CLASS). Grids of mean monthly and mean annual LAI are available from CSIRO Land and Water. The data was produced using empirical relationships between LAI and vegetation in the period 1981-84 determined from satellite images of the visible and near infrared energy reflected by the plant canopy (Lu *et al.* 2001).

Table 10: National land use, land cover and vegetation datasets

Dataset	Custodian	Spatial extent	Year	Spatial resolution	Access	References
National Land Use Mapping	Bureau of Rural Sciences	Australia	1993, 1995, 1997, 1996, 2000, 2002	1:2,500,000	Bureau of Rural Sciences: http://www.brs.gov.au	Stewart *et al.* 2001
Catchment Scale Land Use Mapping	Bureau of Rural Sciences	Australia (incomplete)	Unknown	Varies from 1:50,000 to 1:250,000	Bureau of Rural Sciences: http://www.brs.gov.au	Lesslie *et al.* 2003
Australian Irrigated Areas	National Land and Water Resources Audit	Australia (incomplete)	Unknown		Australian National Resource Data Library: http://adl.brs.gov.au/anrdl/php/basic_search.php	NLWRA 2001b
Land Cover for the Intensive Use Zone of Australia	The University of Melbourne	Intensive use zone of Australia	1990, 1995	1km grid cells	CRC for Catchment Hydrology: http://www.catchment.crc.org.au	Western 2005
Australian Land Cover Change	Bureau of Rural Sciences	Intensive use zone of Australia	1990, 1995	25m, 100m and 250m grid cells	Australian National Resource Data Library: http://adl.brs.gov.au/anrdl/php/basic_search.php	Kitchin & Barson 1998, Barson *et al.* 2000
Integrated Vegetation Cover	Bureau of Rural Sciences	Australia	Post 1997	100m grid cells	Australian National Resource Data Library: http://data.brs.gov.au/asdd/php/basic_search.php	Thackway *et al.* 2004
MDB Baseline Mapping	Bureau of Rural Sciences	Murray Darling Basin	Unknown	1:100,000		
Forests of Australia	National Forest Inventory	Australia	2003	250m grid cells	Australian National Resource Data Library: http://data.brs.gov.au/asdd/php/basic_search.php	
National Vegetation Information System (NVIS)	Australian Government Department of Environment and Water Resources	Australia (incomplete)	Present day and pre-European (Post 1997)	Varies from 1:5000 to 1:1,000,000	Environment Data Directory: http://environment.gov.au/erin/nvis/index.html	
National Plantation Inventory (NPI)	Bureau of Rural Sciences	Australia	2000	250m grid cells	Bureau of Rural Sciences: http://www.brs.gov.au	
Leaf Area Index (LAI)	CSIRO Land and Water	Australia	Mean annual and monthly (1991-94)	0.05 degree (~5km) grid cells	Australian National Resource Data Library: http://adl.brs.gov.au/anrdl/php/basic_search.php	Lu *et al.* 2001

4.5 Irrigation

Irrigation data is a requirement for water balance models such as BiosEquil and BiosEvolve. These models often require information about the area of irrigated crops and pastures. A national-scale map of irrigated areas (‘Australian Irrigation Areas, Version 1a’) was produced as part of the NLWRA in 2000. It was based on boundaries supplied by water management agencies from across Australia. However, the dataset is incomplete. Stewart *et al.* 2001 note that irrigation occurs outside the irrigated areas on the map, and that irrigation does not occur in all irrigated areas identified on the map, particularly in the Murray Darling Basin and Tasmania. Information about irrigated land uses can also be obtained from the national and catchment-scale land use maps (Stewart *et al.* 2001, Lesslie *et al.* 2003).

Information about irrigation applications can be obtained from a number of sources at varying spatial scales and for various years. Regional and national-scale studies of irrigation are summarised in Table 11. The type of information that can be obtained from these studies includes:

- Area irrigated (total and by land use)
- Irrigation allocation
- Irrigation application (total and by land use)
- Cost of water
- Economic returns (total and by land use)

The accuracy of the data differs between studies; most studies provide estimates of data accuracy (e.g. MDBC 2005, NLWRA 2000a). In the 2003/04 MDBC Water Monitoring Report, for example, the accuracy of the irrigation divisions ranges from ±0% for the Wimmera-Mallee in Victoria to ±40% for the Moonie River in Queensland (MDBC 2005).

4.6 Hydrogeology

Hydrogeological data is needed for many complex water balance models with 2-dimensional flow. The typical data requirements include aquifer depth and thickness, water table depth and aquifer properties.

A considerable amount of hydrogeological data can be obtained from traditional hydrogeological maps, which are available in both printed and digital (GIS) format. Brodie 2002 and Brodie *et al.* 2004 provide a review of published hydrogeological mapping in Australia. The ‘Hydrogeology of Australia’ provides the most comprehensive coverage of the Australian continent including information about aquifer type, lithology, salinity, potentiometry, flow systems and abstraction for Australia’s principal aquifers (Lau *et al.* 1987). However, this map has some shortcomings. Firstly, at a 1:5 million scale, it has a very coarse spatial resolution. Furthermore, some important information is missing from the dataset, such as a national coverage of the water table. However, hydrogeological maps, at a finer resolution, are available for the large Australian basins including the ‘Hydrogeology of the Great Artesian Basin’ (Habermehl & Lau 1987), the ‘Hydrogeology of the Darling Basin’ (Williams *et al.* 1994) and the ‘Hydrogeology of the Murray Basin’ (Cooper 1994, Evans 1992). In addition, other hydrogeological maps have been developed for specific purposes including salinity (NLWRA 2000b) and groundwater flow systems (Coram *et al.* 2000) maps.

Table 11: Selected studies of water use by irrigated industries in Australia

Agency	Study	Boundaries	Coverage	Years	Reference
ABS	Agricultural Statistics	Statistical Local Area Statistical Division State/Territory Australia	Australia	1992/93- 2003/04	ABS 2004
ABS	Water Account for Australia	State/Territory Australia	Australia	1993/94- 1996/97	ABS 2000
ANCID	Annual Benchmarking Data Reports	Irrigation system	Australia	1997/98- 2003/04	ANCID 2005
AWRC	Review of Australia's Water Resources and Water Use	River Basin	Australia	1983/84	AWRC 1987
MDBC	Water Audit Monitoring Report	Catchment Management Region	Murray Darling Basin	1997/98- 2003/04	MDBC 2005
NLWRA	Australian Water Resources Assessment	Surface Water Management Area River Basin	Australia	1986/87	NLWRA 2000a
CSIRO	Quantifying and Valuing Land Use Change for Integrated Catchment Management evaluation in the Murray-Darling Basin 1986/87 – 2000/01	Catchment Management Region	Murray Darling Basin	1986/87- 2000/01	Bryan & Marvanek 2004
CSIRO	Water Use Statistics	Statistical Division State/Territory Australia	Australia	1992/93	Dunlop 2001
CSIRO	REFIRR	Various	Australia	Various	Humphreys *et al.* 2003

Groundwater data was also collected as part of the NLWRA in 2000. The data is summarised to Groundwater Management Units (GMUs) and Groundwater Provinces. The type of data available includes groundwater use and sustainable yield (NLWRA 2000a).

State and territory agencies maintain databases of groundwater bores and bore logs. A wide range of physical and chemical data is available through these databases, although it is difficult to access data for large regions from some databases. The most common physical data are location, elevation, water level, lithology and aquifer. In terms of chemistry data, the databases often contain salinity, concentrations of major elements, pH and TDS. There are a number of limitations associated with these groundwater databases. Firstly, some databases do not contain information about the aquifers that the bores are intercepting. Secondly, some databases are not updated regularly. For example, the version of the Victorian Groundwater Database available on the web was last updated in June 2002 (DSE 2002). Some of these problems may be overcome by the Australian Water Data Infrastructure Project (AWDIP), a national distributed database network of bore and stream gauge data that will be available to the public in 2005. The AWDIP interface will have limited access to groundwater data in the first instance, primarily groundwater level and salinity where accessible (Bleys 2005).

4.7 Water quality

In terms of water quality, salinity is the most common data requirement for water balance models; it is also most readily available. Water quality data for surface water and groundwater resources is collated into databases held by state and territory agencies. Refer to Brodie *et al.* 2004 for a comprehensive review of these databases. Water quality data is also monitored by other water management agencies, such as irrigation authorities, but is often difficult to access. A national coverage of water salinity will soon to be available through AWDIP (Bleys 2005).

Additionally, groundwater salinity contours are presented on hydrogeological maps including the 'Hydrogeology of the Murray Basin' (Cooper 1994, Evans 1992) and the 'Hydrogeology of the Great Artesian Basin' (Habermehl & Lau 1987).

Soil salinity measurements are available for some of the soil profiles contained within ASRIS. According to Johnston *et al.* (2003), there are 82,650 salinity measurements in the ASRIS database.

Rainfall chemistry data is input to a number of water and salt balance models, such as CATSALT, CLASS and SWAGSIM. Despite this, rainfall chemistry data is not routinely collected in Australia. Although regional studies of rainfall chemistry have been undertaken, the coverage of Australia is incomplete. Published data is available for some parts of Australia (Table 12).

Table 12: Selected studies of rainfall chemistry in Australia

Study	**Location**
Blackburn & McLeod 1983	Murray-Darling Basin
Keywood *et al.* 1999	Western and central Australia
Kellett *et al.* 2003	GAB recharge beds, Queensland
Hingston & Gailitis 1976	Western Australia
Kayaalp 1999	South Australia

4.8 Topography and hydrological mapping

Digital Elevation Models (DEMs) are a common requirement for distributed water balance models, such as CLASS and TOPOG. National DEMs are available from Geoscience Australia: the 8-second DEM provides a complete coverage of Australia, while the 3-second and 19-second DEMs are only available for selected parts of Australia.

Catchment boundaries are needed to calculate flow volumes at outlets from distributed models, or to summarise spatial input data for lumped models. Geoscience Australia (GA) provide catchment boundaries including Australia's River Basins (1997), which divides Australia into 12 drainage divisions, 77 water regions, and 245 river basins. Boundaries for surface water management areas are also available from GA. A hierarchy of nested catchment boundaries is available from the Centre for Resource and Environmental Studies (CRES).

Four levels of catchments and subcatchments are available based on minimum area thresholds of 2.5 km^2, 25 km^2, 50 km^2 and 500 km^2 (Hutchinson *et al.* 2000).

Topographic mapping may be needed to characterise surface water features within the study region. GA undertakes topographic national-scale mapping as part of their NATMAP and GEODATA series (GA 2005). A variety of themes are available from the topographic maps including infrastructure, drainage, relief and vegetation at varying spatial resolutions. Complete coverage of Australia is available at a 1:1 million, 1:2.5 million, 1:5 million and 1:10 million resolution; incomplete coverage of Australia is available at a 1:100,000 and 1:250,000 resolution. State and territory agencies provide topographic mapping at a finer resolution. Refer to Brodie *et al.* 2004 for a more detailed review of hydrological mapping in Australia.

4.9 Other

Some water balance models have very specific data requirements. For example, CLASS requires outputs from other models including the FLAG Upness Index and MRVBF Index. It is beyond the scope of the present review to discuss the availability of non-standard data required by specific models. The reader is referred to articles and manuals for specific models for further information about the availability of non-standard datasets (e.g. Tuteja *et al.* 2004 for CLASS).

5. Model performance and limitations

This section provides a review of the application and performance of water balance models in Australia over the last three to four decades. While every effort has been made to provide a comprehensive review, the authors acknowledge that there may be other work, in both published and unpublished forms, not accounted for in this section. A summary of water balance model applications is given in Table 13.

5.1 Single-layer simple models

Simple water balance models incorporating a single soil layer assume vertically and horizontally homogeneous soil and thus, the entire soil or root zone is assumed to be a single soil layer. By comparison, simple models with multiple soil layers are able to incorporate the vertical heterogeneity of soil.

The improved version of WATBAL is still in use in the regional wheat yield forecasting model, STIN. WATBAL is also extensively used in the northern pastoral region to derive soil water balance and plant growth.

GrowEst has been widely used as a climate filter for plant growth and tested and adapted over almost 40 years at different institutions. This has included reviewing and refining the functions and relating them to available data sets and the associated literature, thereby providing an interim level of validation. GrowEst models need few input parameters and have a simple model structure that increases transportability of the model from one region to another. Most climate and soil input data for GrowEst are available both in point and spatial form across Australia.

In addition to the features found in WATBAL and GrowEst, PRIDE calculates irrigation requirements and ET using the FAO method, which in turn requires some plant-specific parameters such as crop coefficients and potential ET. Although crop coefficients vary from region to region, generic values have often been used (Allen *et al.* 1988). PRIDE performs well under conditions where the crop water requirements and the farmer irrigation practices are well known (White and Walker 2000). It is suitable for the prediction of irrigation demands under changing landuse scenarios. PRIDE can also be integrated with other water resource allocation models such as REALM. PRIDE has been tested and applied in a couple of locations in Victoria and NSW.

Although BiosEquil consists of a single soil layer, it contains more processes than WATBAL, GrowEst and PRIDE such as soil evaporation, interception evaporation, subsurface runoff and subsurface drainage. As a result, BiosEquil requires more parameters and climatic variables, most of which are, either available or are in the process of developing spatially. In addition to that, the modelling structure for BiosEquil is also not as simple as the other simple models described above. It employs the Priestley-Taylor equation, which, unlike the Penman-Monteith equation, does not require vapour pressure deficit and wind speed to calculate ET. In addition to water balance, BiosEquil estimates carbon, nitrogen, phosphorus as well as net primary productivity of the Australian landscape. It has been used for the NLWRA (NLWRA 2001a).

AWBM model is adapted for use on both gauged and ungauged catchments (Boughton 2004). In the runoff estimation project of the NLWRA, AWBM has been calibrated for 231 catchments in Australia (Boughton and Chiew 2003). This model has been directly compared with the SFB model (Sharifi and Boyd 1994), the USDA SCS curve number method

(Boughton 1995), the PDSMM (Muncaster *et al.* 1997) and an auto-regressive mathematical model (Metcalfe *et al.* 2002) and the results generally favoured the AWBM.

5.2 Multiple-layer simple models

Since duplex soils are second only to sandy soils in their dominance in the Australian continent, it is understood that the use of at least two-layer models could improve estimates of water balance. Two-layer or multi-layer cascading water balance models are essentially an expansion of single-layer models, but are able to effectively capture vertical variability of soil features.

In an attempt to increase the model performance and versatility, the time-dependent version for BiosEquil (BiosEvolve) is being developed from the steady-state model. In line with duplex soils in Australia, dividing the water store into two unsaturated soil pools (Greacen and Hignett 1976, Irannejad and Shao 1996) in BiosEvolve can be well justified.

Of the CERES family, PERFECT is one of the most widely-used models. PERFECT has been validated widely (Abbs 1994, Carroll *et al.* 1992, Freebairn *et al.* 1991, Gardner *et al.* 1995, Grundy *et al.* 1992, Hayman 1992, Hayman and Kneipp 1995, Lawrence and Littleboy 1990, Littleboy *et al.* 1992b, Littleboy *et al.* 1992c, Littleboy *et al.* 1996a, Littleboy *et al.* 1996b, Littleboy *et al.* 1999, Thomas *et al.* 1995). This model has the capacity to analyse the effect of crop sequences and fallow management on the water balance, as well as runoff and soil erosion in crop growing areas of the sub-tropics of Australia. It also includes processes such as soil evaporation, infiltration and transpiration (leaf area and soil moisture). PERFECT can perform well in situations where it simulates the crop and fallow phases of a range of cropping systems, particularly of wheat, sorghum and sunflower.

APSIM users can use either SoilWat or APSWIM and as a result, APSIM enables these contrasting approaches to be compared readily (McCown *et al.* 1996). The SoilWat module in APSIM is an improved version of PERFECT. Since APSIM has detailed modules for crops, cash crops and pastures, SoilWat has the additional advantage of a capacity to analyse water balance dynamics under various crops and pasture regimes, especially at paddock scale. The APSIM was found to reproduce closely the water balance measurements from several sites in the cereal belt. It is also suggested that the APSIM is a valid tool for evaluating the impact of changes to cropping systems and agronomic practices on the water balance of dryland regions (Verburg and Bond 2003).

GRASP has been implemented in a spatial framework known as AussieGRASS. This modelling framework was used initially for native perennial pastures in northern Australia (Carter *et al.* 1996) and then used for southern temperate pastures (Tupper *et al.* 2001). Remote sensing data are also used to parameterize GRASP in AussieGRASS.

The BASINMAN is the only model (in this review) that uses the Houghoudt equation for drainage calculation, because it is used to design and manage on-farm basin systems. BASINMAN testing against field data from the Murrumbidgee irrigation area has shown that the model can simulate actual conditions reasonably well in this region at least. BASINMAN has been compared with SWAGMAN Destiny and found that the results of the simulations from the two models are comparable in most aspects (Wu *et al.* 1999). Compared to SWAGMAN Destiny, treatment for irrigation scheduling is slightly different in BASINMAN where it maintains a rain delay that enables better use of rainfall (Wu *et al.* 1999).

CATSALT deals with catchment scale salt balance and contains the soil moisture accounting and routing model (SMAR). Potential ET is calculated in this model from a conversion of pan evaporation and simple empirical relationships have been employed to link ET with land use.

Similar to CLASS, the effect of topography in CATSALT is accounted for with a wetting index to disaggregate surface runoff within a given region. CATSALT can be used to model land use changes on water quantity and quality. CATSALT has a soil moisture component and can be linked to groundwater models. Outputs from CATSALT can be input to flow system models e.g. IQQM. CATSALT has been tested in approximately 150 catchments in New South Wales including the uplands areas of the Murray-Darling Basin, the Hunter and three other coastal catchments: Murrumbidgee (Tuteja *et al.* 2000); Border Rivers, Gwydir, Castlereagh, Macquarie, Lachlan, Murrumbidgee and Murray Rivers (Beale *et al.* 2000); Kyeamba Valley (Tuteja *et al.* 2002); Mandagery Creek (Tuteja *et al.* 2003) and Boorowa River (Vaze *et al.* 2004). CATSALT has been used by the NSW Department of Infrastructure, Planning and Natural Resources (NSWDIPNR, formerly NSW Department of Land and Water Conservation) since 1999 to inform the NSW Salinity Strategy and the Murray Darling Basin Salinity Audit.

IQQM, REALM and MSM-BIGMOD have been developed for water flow assessment and resource management. IQQM is intended for use in investigating the impacts of water resource policies or policy changes on stakeholders, particularly in New South Wales and Queensland. The shell structure of IQQM easily allows new modules to be incorporated into the existing structure. SAC-SMA is the soil water component of IQQM.

IQQM can be used to model complex scenarios of water management including demand modelling, water ordering, annual accounting, continuous accounting and capacity sharing. The model can be applied to both regulated and unregulated river systems and used to model both water quantity and quality. It has been successfully implemented in catchments across New South Wales and Queensland.

IQQM has already been applied to studies of land use and climate change (see Herron *et al.* 2002) and implemented in major river systems in New South Wales and Queensland including Border Rivers, the Clarence, Fitzroy, Hunter, Lachlan and Macquarie river systems. It has also been implemented in smaller systems such as parts of the Snowy and Tooma rivers, and the Cox’s river, and has been used to investigate options for salinity routing in several New South Wales river systems. IQQM is currently being implemented by the Murray-Darling Basin Commission for the Murray River. Internationally, it has been applied in Indonesia, South-east Asia (Mekong River) and Zambia.

REALM is similar to IQQM in terms of purpose. REALM is in active use in Victoria, South Australia and Western Australia for water allocation modelling, analysing the yield and security of water supplies and evaluating changes in operation of stream flows (Schreider *et al.* 2003a and 2003b). The MDBC uses MSM-BIGMOD model to establish operating rules for storages, irrigation demands, water resource assessment and water accounting, and flow and salinity routing. It can also be used for examining policy and management scenarios in relation to water quality and quantity. This model can also provide some economic information, such as the value of irrigation, value of power generation, the cost of salinity to users and flood costs. MSM-BIGMOD has been tested by comparing flow and salinity outputs from the model with observed flow and salinity at various gauging stations in the Murray River system. MSM-BIGMOD is operational in the Murray River system from Dartmouth Dam to the Murray Mouth; it is used routinely by the MDBC for testing management and planning scenarios, such as environmental flows, the cap, water accounting, and flow and salinity routing.

5.3 Limitations of simple models

Simple models trade off many important soil and water-related plant processes. Some simple models assume soil evaporation is negligible compared to plant transpiration. However, this is not the case in early stages of crop growth. WATBAL, GrowEst and PRIDE use ET that accounts for both plant and soil evaporation. Not many simple models account for interception evaporation from the canopy. However, this may not be a significant effect for crops with low leaf area indices.

It is known that maximum soil water storage capacity becomes greater with increasing effective rooting depth as a plant grows. Although the increase storage capacity may not be directly proportional to the rooting depth, simple soil water models often do not have the structural capacity to consider varying soil water storage capacity to reflect water uptake by plants. Some models, such as WATBAL and GrowEst, do not have root components in the water balance analysis.

Multilayer simple models such as PERFECT and APSIM (SoilWat) have been used in a GIS framework to investigate impacts of land management practices on the near surface water balance dynamics and water balance components. However, there are limitations between the catchment scale fluxes and those obtained in a simple, vertical water balance analysis due to spatial scale effects and lack of accounting for lateral flows in these models.

Simple models with a bucketing approach do not capture the key processes governing deep drainage such as the lack of distinction between surface runoff and deep drainage and the exclusion of low permeability sub-soil constraints. Therefore, they do not necessarily provide enough information to evaluate the impacts of land use and land use changes on deep drainage (Walker *et al.* 2002).

5.4 Complex models

Models with continuous flow are treated as complex and have either one or two-dimensional water flows. Complex models are used for detailed studies of water movements. They simulate runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching within the location where they apply.

SWIMv1 uses Richards' equation with an efficient numerical solution. SWIMv1 was found to predict water flow well under the near-saturated conditions tested (Bond 1994, Bond *et al.* 1993). Schwamberger (1995) also tested the accuracy of SWIMv1 in estimating upflow from static watertables, by comparing values with data sets obtained in lysimeter studies under different crop, soil and watertable-depth combinations. The model was capable of simulating upflow with an acceptable degree of accuracy provided that parameters describing plant leaf area and, particularly, root distribution were adjusted appropriately (White and Walker 2000).

SWIMv2 includes a numerical solution for the advection-dispersion equation. SWIMv2 tested against measured water contents (Bond 1994, Bond *et al.* 1993, Bond *et al.* 1997, Verburg *et al.* 1996) and found that the model provided acceptable predictions. However, the lack of interaction with plants means that the standalone SWIM is not suited in itself to regional analysis of plant productivity (White and Walker 2000). Therefore, incorporation of SWIMv2 into the APSIM modelling shell (APSWIM) has been useful to analyse plant productivity in relation to water. When appropriate data are available and conditions meet model assumptions, APSWIM can be applied anywhere.

WAVES predicts the dynamic interactions within the soil-vegetation-atmosphere system. Unlike other complex models described above, WAVES includes the processes that control transpiration physiologically. As a result, it has the capacity to predict water dynamics under landuse change. WAVES is used to predict recharge under current and proposed land uses over a range of climatic and geologic zones to help predict land areas at risk from salinisation.

The land surface parameterisation scheme, ALSIS, is a GIS framework that can be connected to one-dimensional water flow model and developed to predict soil moisture over the Australian continent. Irannejad *et al.* (1997) applied ALSIS to assess the impacts of vegetation cover on the soil water budget and found that increased vegetation cover increases total surface ET and decreases runoff and recharge. ALSIS has been applied for soil moisture simulation over the Australian continent (Lyons *et al.* 1997, Irannejad and Shao 1999). Although the initial result of the model is shown to perform reasonably well, it is suggested that further parameterisation is required to improve the agreement between simulated and observed soil moisture.

Topog_Yield can be used to simulate hydrologic states over long-term sequences, characterised by variable climatic conditions and land use. TOPOG_Yield was tested in the north Maroondah experimental area, located in the central Victorian Highlands for runoff over a continuous 12 year period. Modelled and observed daily runoff values compared well (Vertessy *et al.* 1993). TOPOG_Yield is one of the models that has soil water component connected to forest hydrology. In terms of performance, modelled and observed runoff values compared well (Vertessy *et al.* 1993). TOPOG_Yield can only be applied to catchments where extensive hydrological data are available and as a result, Topog_Yield has not been applied widely because it requires catchment-specific data that are not readily available. Vertessy *et al.* (1996) applied Topog-IRM to the Picaninny catchment in the Central Highlands of Victoria, Australia and found that predicted soil water storage agreed well with field observations.

CLASS is a spatial modelling framework with a soil water module including groundwater discharge and recharge model. It also contains crop and pasture models. CLASS has a good potential to analyse catchment-scale land use effects on water dynamics. The CLASS model is intended for implementation on medium to large sized catchments to investigate the effects of land use and climate variability on catchment scale. CLASS is currently being used in Landscape Strategy for the Snowy Monaro region, the MDBC Salinity Audit (2004/05) and the Grains Resource and Development Corporation (GRDC) funded CSIRO, DPI NSW and DIPNR project on the catchment scale land use effects in the Simmons Creek catchment (Billabong, Murray). Considerable effort has been made in representing vegetation growth, as well as in the pathways that water takes from hill slopes to stream. This capability enables detailed simulation of the effects of different management scenarios. CLASS includes a user-friendly interface to assist the user in preparing the data needed for execution and testing. It has a powerful platform for detailed analysis and makes excellent use of the available data. The model also includes comprehensive hydrology and growth components. The growth model includes annual and perennial pastures (C3 and C4) along with legumes, cropping and trees.

The SWAGSIM/SWAGMAN series has been developed to determine spatial response of watertable to recharge rice fields, and has been applied widely in the Murrumbidgee irrigation area. In addition to water table fluctuations, SWAGMAN Farm also deals with salinity and economics of the farm; additional data is needed to model these processes. In addition to features of SWAGMAN Farm, SWAGMAN Destiny can determine crop productivity. SWAGSIM was designed specifically for irrigation areas with shallow water tables. It assumes that a land unit has a single land use, with rain and irrigation applied uniformly within this unit and therefore farms are subdivided into smaller units to reflect homogeneous land-use and irrigation practices. It also has a regional component incorporated into the model.

Calibration and validation of the SWAGSIM and SWAGMAN Destiny models has been conducted under a range of conditions with fairly satisfactorily results (Timsina *et al.* 2000). Weighing lysimeter experiments (Meyer 1988, Meyer *et al.* 1990, Smith *et al.* 1993, Smith *et al.* 1996) have been used for early testing of the model. Experiments on irrigated pastures overlying shallow saline water tables (Meyer *et al.* 1995) and on perennial horticultural crops irrigated with saline water in Victoria have also been used for validation of the model.

SWAGSIM has been successfully used to determine the impact of rice growing in the Murrumbidgee Irrigation Area of New South Wales, to evaluate the feasibility of using shallow groundwater pumps to control water tables, to evaluate subsurface drainage options for the Mead Ridge project area in Victoria, and to evaluate groundwater discharge into the Hunter River of New South Wales. Simulations of SWAGMAN Destiny showed good agreements with observed data from wheat and rice growing areas (Smith and Humphreys 2001). SWAGSIM and SWAGMAN models in general have been extensively tested in irrigated conditions and with and without groundwater tables. Edraki *et al.* (2003) stated that these models are reliable predictors of water table behaviour and crop performance in irrigated areas, provided appropriate model inputs are given.

5.5 Limitations of complex models

As stated earlier, complex models in this review are basically defined as models that use Richard's and Darcy's equations. Richard's equation assumed that the soil is incompressible, non-hysteretic and isothermal, and that moisture moves in a single phase soil matrix only, and not via macropores and larger preferred pathways (Zhang and Dawes 1998). Therefore, solutions of the Richards' equation do not necessarily replicate water balance dynamics more accurately. Like any other complex processes, Richards' equation has also inherited issues related to its calibration for many soils. In addition, the pressure of cracking, poor weathering and self-mulching means that Richards' equation does not simulate the soil moisture dynamics well (Walker *et al.* 2002). In the application of Darcy's law in some models such as WAVES, the soil is assumed to be isotropic for lateral water movement. Soil air flow is also ignored (Zhang and Dawes 1998).

Although complete validation of any model is vital for confident use, it is sometimes not possible with complex models. In such situations the emphasis should be on reviewing and refining the functions and relating them to available data sets and the associated literature, thereby providing an interim level of validation.

Table 13: Summary of model applications in Australia

Model (Developer)	Enterprise	Location/Industry	Scale	Operational status	Reference
WATBAL (ANU/CSIRO)	Simple water balance calculations	In regional wheat yield forecasting model (STIN)	Spatial	Currently used	Stephens 1995
PRIDE	District irrigation water demand	Goulburn Murray water	Point	Currently used	Erlanger *et al.* 1992
GROWEST (ANU) GROWEST Plus (BRS)	EC applications	BRS	Spatial	Currently used	Hutchinson *et al.* 2002, Brinkley *et al.* 2005
BiosEquil (CSIRO L&W)	Long-term averages of H_2O, C, N and P	National Land and Water Resources Audit	Spatial	Currently used	Raupach *et al.* 2001
	National water balance study – Water2010	BRS		Currently used	
PERFECT (DLWC NSW)	Erosion-productivity relationships	For Wheat	Point		Littleboy *et al.* 1992a
		For Alfisols in the semi-arid zone			
	Evaluating the effects of cropping systems on runoff, erosion and yield	Gunnedah, NSW			
		Liverpool plains, NSW			
	Evaluating surface management options	Semi-arid tropics and subtropics			
		For Alfisols in the semi-arid zone			
	Evaluating the effects of crop and pasture rotations on runoff, erosion and drainage	Central Queensland			
SACRAMENTO (US National Weather Service)	A component of IQQM	DLWC NSW	Spatial	Currently used	Burnash 1985
IQQM (DLWC NSW & QDNR)	Investigating the impacts of water resource management policies or policy changes	Border Rivers, the Clarence, Fitzory, Hunter, Lachlan and Macquarie river systems	Spatial	Currently used	DLWC NSW

Table 13 (cont')

Model (Developer)	Enterprise	Location/Industry	Scale	Operational status	Reference
CATSALT (DLWC NSW)	Land-use change and climate variability on the water and salt balance at a catchment scale	Murrumbidgee, Border Rivers, Gwydir, Castlereagh, Macquarie, Lachlan, Murrumbidgee, Murray Kyeamba Valley, Mandagery Creek, Boorowa River	Spatial		Tuteja *et al.* 2002
	NSW Salinity Strategy and the Murray Darling Basin Salinity Audit	DLWC NSW		Currently used	
BASINMAN (CRC CH)	To evaluate hydraulic relationship between the farmed area and the basin system to control water logging	Murrumbidgee irrigation area, NSW	Point		Wu *et al.* 1999
SWIMv1 (CSIRO L&W)	Prediction of contaminant leaching from land irrigated with uranium mine waste water	Alligator Rivers Region	Point		Ross 1990b
SWIMv2 (CSIRO L&W)	Salt and nitrate leaching to the groundwater following effluent irrigation	Wagga Wagga	Point		
WAVES (CSIRO Water Resources)	Predict recharge under current and proposed land uses over a range of climatic and geologic zones to help predict land areas at risk from salinisation	Natural Resources Management Strategy (funded by the MDBC) for Victorian State agencies	Point		Dawes and Short 1993
		Hillston (NSW), Walpeup (VIC)			Zhang *et al.* 1999a
		Loddon-Campaspe catchments (VIC)			Salama *et al.* 1999
		Griffith (NSW)			Zhang *et al.* 1999b
		Chowilla (SA)			Slavich *et al.* 1998
		North Stradbroke island (QLD)			Green *et al.* 1997a
		Swan coastal plain (WA)			Green *et al.* 1997b

Table 13 (cont')

Model (Developer)	Enterprise	Location/Industry	Scale	Operational status	Reference
APSIM water balance module (APSRU, Qld)	prediction of crop growth in terms of water balance dynamics	Widely used in several cropping systems	Point	Currently used	McCown *et al.* 1996
Topog_Yield in Topog (CSIRO Water Resources)	Catchment-based model for unsaturated/saturated flow and evapotranspiration	Myrtle II catchment, Central Vic Highlands, CSIRO Water Resources and Melbourne Water	Spatial		Vertessy *et al.* 1993
ALSIS (UNSW)	Land surface parameterisation scheme	Model development	Spatial		Irannejad and Shao 1996
	Soil moisture modelling and prediction	Australian continent (UNSW and BRS)			Lyons *et al.* 1997
	The impacts of vegetation cover on the water balance budget	Goodlands region, WA			Irannejad *et al.* 1997
CLASS (DIPNR NSW)	To investigate the effects of landuse and climate variability on catchments, and a range of environmental problems	Landscape Strategy for the Snowy Monaro region, MDBC Salinity Audit 2004/2005	Spatial	Currently used	Tuteja *et al.* 2004
	Catchment scale landuse effects in the Simmons Creek catchment	Billabong Murray, GRDC funded CSIRO, DPI NSW and DIPNR project		Currently used	
SWAGSIM (CSIRO Land & Water)	To evaluate management options for shallow water tables	Murrumbidgee Irrigation Area, NSW	Point		Meyer and Prathapar 1992
SWAGMAN Options (CSIRO Land & Water)	To identify profitable non-rice-land uses which component rice growing and induce discharge from shallow water tables without exceeding critical levels of soil salinity	Camarooka project area, NSW			Prathapar *et al.* 1997
	Impact of rice growing on water table	Murrumbidgee Irrigation Area, NSW			
	To evaluate subsurface drainage options	Mead Ridge project area, VIC			
	To evaluate groundwater discharge into the Hunter River	NSW			

6. Towards a modelling framework for Water 2010

The background and goals of the Water 2010 project have already been discussed in some detail in Chapter 1. The specific objectives of the project are:

- To ensure information requirements are met to assess progress on addressing over-allocation and overuse across all river basins.
- To assess the significance of water intercepting activities on catchments and aquifers based on an understanding of the total water cycle, and help monitor the progress of catchments and aquifers towards either full allocation or the threshold level of interception.
- To work with the ABS, the MDBC and the NWC on the development and implementation of water resource accounts that can be reconciled annually and aggregated to produce a national water balance covering all significant water use, including groundwater systems.
- To develop systems that can explore likely or desired changes and trends in the water balance at a national and catchment level as a result of events such as climate change, landuse change, social change and the implementation of new policies and practices.
- To provide a scientific framework to support co-management of groundwater and surface water resources.

The project aims to answer the following questions regarding water supply in Australia, among others:

- How much water (surface and ground) can a region (drainage basin, catchment, sub-catchment, valley) hold if ‘full’?
- How much recharge of surface and ground water is there in a region in a normal month, season or year? Wet month, season or year? Dry month, season or year?
- How reliable is surface and groundwater recharge in a region?
- What is the relative impact of different land uses in a region on surface and groundwater yield?

To achieve these aims and answer these questions, with respect to surface water at the very least, the selection and/or development of an appropriate water balance model is required. There are a range of reasons why so many water balance models are currently in use. A major factor is the variation in scale at which water balance simulation is made. Simple models are useful in large scale modelling where a lack of data and limits in understanding of all the factors and processes affecting water dynamics hampers the application of complex models. However, since simple models do not capture all the relevant processes, particularly in short time periods in the water balance system, a fine balance between available data and model simplicity/complexity should be sought in line with project objectives.

Six catchment-scale water balance modelling approaches were selected for further consideration of their ability to contribute to the Water 2010 project:

- BiosEquil / BiosEvolve

- AussieGRASS (GRASP)
- Australian Water Balance Model (AWBM)
- CATSALT
- TOPOG
- CLASS

6.1 Evaluation of modelling approaches

As highlighted by the CRC for Catchment Hydrology, the project objective is one of the most important considerations in choosing the right model for a given purpose (CRC-CH 2000). For Water 2010, the project objective is to provide nationally-consistent information on the water balance, including rainfall, ET, runoff and deep drainage, for use in strategic planning. With this in mind, the six catchment water balance modelling approaches listed above are examined here with respect to data requirements, modelling processes and paradigm currency, and national applicability.

6.1.1 BiosEquil and BiosEvolve

BiosEquil and BiosEvolve were developed in 2000. Both models use the Priestly-Taylor equation to calculate potential ET and the Budyko (1974) equation to calculate actual ET (after Zhang *et al.* 1999). Zhang *et al.* (2004 and in press) report recent improvements in the calculation of ET. There is potential to incorporate these improvements into the BiosEquil modelling approach.

In BiosEquil and BiosEvolve, the water balance comprises precipitation, transpiration, soil evaporation, surface and subsurface runoff, and deep drainage for the pixel-based soil root zone. Each pixel has a prescribed amount in the soil water storage and has a single landuse. Runoff is calculated using the water balance approach (Raupach *et al.* 2000a, Raupach *et al.* 2000b).

BiosEquil and BiosEvolve are both distributed models that produce gridded outputs. As part of the NLRWA, the outputs from BiosEquil were summarised to the 245 River Basins and 12 Drainage Divisions (Raupach *et al.* 2001a). However, these models do not take into account the hydrological consequences of aggregating to different boundaries, such as transmission losses, flow routing and base flow.

All input datasets for BiosEquil are readily available at a national-scale. The model has been already applied at the national-scale as part of the NLWRA (Raupach *et al.* 2001a, Raupach *et al.* 2001b), although the outputs were not rigorously validated. The dynamic version of the model, BiosEvolve, has not been applied at national-scale. BiosEvolve has additional requirements for meteorological and soil data, which are available through SILO PPD and ASRIS respectively.

BiosEquil uses land use as an input and therefore could be used to model the effects of land use change. In their application of BiosEquil across the continent, Raupach *et al.* 2000 only used a single alpha factor, the parameter that defines the curvature in the relationship between rainfall and ET, for all land uses. However, there is potential to parametise the alpha factor for land use based on soil rooting depth (after Zhang *et al.* 1999).

As BiosEquil is a quasi-steady-state model, there are issues associated with modelling the transient responses of landscape, particularly at the monthly scale. There is, however, potential to incorporate recent developments regarding storage fluxes into this modelling approach (after Zhang *et al.* 2005). BiosEquil does not have a flow routing option, but an additional module could be developed to improve the estimation of runoff at the catchment outlet to account for transmission losses, base flow, topography and catchment position.

6.1.2. AWBM

AWBM is a simple daily rainfall-runoff model that was developed in the early 1990s. A simple water balance approach is used to estimate runoff from daily or hourly precipitation and mean monthly areal potential ET. It uses a pattern of surface storage capacities and partial areas that allow the runoff generating part of the AWBM to be represented by a single runoff characteristic (Boughton and Chiew 2003).

The AWBM is a lumped model, which calculates the water balance at catchment level. Model inputs and outputs are spatially averaged across the catchment. AWBM does account for the spatial variability of surface storage capacity by introducing three partial areas and corresponding capacities. Boughton (2004) reports that an extension to allow for the input of distributed rainfall is in development.

The main limitation of AWBM is that it does not calculate ET; actual ET must be entered into the model. As a lumped model, inputs and outputs are spatially averaged across the catchment (Boughton 2004). The averaging of climate data can be problematic, particularly for large catchments with strong rainfall gradients. Boughton (2004) reports that an extension to allow for the input of distributed rainfall is in development. An important feature of AWBM is the ability to account for baseflow when predicting streamflow by using a Base Flow Index (proportion of total flow that is baseflow), which is estimated from stream hydrographs. Baseflow is ignored in many simple rainfall-runoff models, such as the USDA Curve Number model.

Another feature of AWBM is the routing of rainfall excess in larger catchments. Rainfall excess is routed though a surface store to account for the lag time between rainfall and the appearance of runoff at the catchment outlet. There is also a version of the model that accounts for transmission losses (Boughton 2004). Another recent improvement to the AWBM is the parametisation of the model for ungauged catchments (Boughton and Chiew 2003; see above discussion). However, Boughton and Chiew (2003) advise that this version of the model is not suitable for small, agricultural catchments.

6.1.3. AussieGRASS (GRASP)

AussieGRASS is a national framework, which is routinely used for national-scale modelling of pasture growth, biomass, curing index and grass fire risk index (Carter et al. 2000, Hall et al. 2001). These outputs are available on the Long Paddock website (QDNRM 2005). AussieGRASS also simulates components of the water balance including runoff, soil moisture and deep drainage (Hall et al. 1997), although these products are not available on the Long Paddock website.

In GRASP, the model underlying the AussieGRASS spatial framework, runoff is calculated using two methods. The original Scanlan method is an empirical function of groundcover, daily rainfall, rainfall intensity and soil moisture deficit. This method was developed for the Burdekin catchment, but has been applied in other areas (Scanlan *et al.* 1996). More recently a modified USDA Curve Number approach has been incorporated into GRASP (Owens *et al.* 2003). The Curve Number approach used in GRASP is taken from the PERFECT model (Littleboy *et al.* 1999), which calculates runoff as a function of daily rainfall and soil water contents weighted by soil depth using three parameters that describe the runoff potential for bare soil and runoff response for a particular soil, vegetation and management. AussieGRASS is similar to BiosEquil in that it also has gridded outputs (Carter *et al.* 2000).

The AussieGRASS framework and the underlying GRASP model are designed to operate in rangeland environments. For example, in a study of deep drainage in the Queensland part of the Murray Darling Basin, the GRASP model was only used in rangeland areas while PERFECT was used to model deep drainage in cropping areas (Yee Yet and Silburn 2003).

AussieGRASS does not use the water balance equation to calculate runoff; it is calculated using either an empirical equation (the Scanlan method) or the USDA Curve Number. The later approach is very sensitive to the choice of curve number, which is best calibrated against stream flow data. Similar to BiosEquil and BiosEvolve, the AussieGRASS modelling paradigm does not overtly include flow routing.

Most input data for AussieGRASS are available for the continent. Meteorological data are sourced from SILO PPD. AussieGRASS also requires spatial information on soils, pasture type, stocking rates and tree cover. The Queensland Department of Natural Resources and Mines (QDNRM) have collected and standardised data from a range of sources, such as the ABS and field work, to form a national input dataset. AussieGRASS has been parametised for a wide range of agro-ecological zones including tropical C4 pastures (Carter et al. 2000), southern pastures of New South Wales, South Australia and Western Australia (Richards et al. 2001), high rainfall zone temperate pastures (Tupper et al. 2001) and the Northern Territory and Kimberley rangeland (Dyer et al. 2001). QDNRM also developed new datasets where data was not available. For example, Danaher et al. (1992) developed a technique to estimate tree basal area from NOAA NDVI and field measurements.

The USDA curve number approach, used by AussieGRASS to predict runoff, requires stream flow data to estimate runoff parameters (Owens et al. 2003). Lack of stream flow data in many Australian river basins may limit the application of AussieGRASS as a national water balance model. However, some research has been undertaken to estimate runoff parameters without calibration against stream flow data (e.g. Littleboy et al. 1996c).

6.1.4. CATSALT

CATSALT is a quasi-distributed model. Runoff is calculated using a lumped rainfall-runoff model (SMAR), and distributed into grid cells based on topographic and land use indices. (O’Connell *et al.* 1970, Kachroo 1992, Tuteja *et al.* 2002). SMAR calculates evaporation for multiple soil layers, which contain a prescribed amount in the soil water storage. Runoff is calculated using the water balance equation, and then transformed to discharge at the catchment outlet using a Gamma Function Model (Nash 1960).

CATSALT attempts to account for the effect of topography by using TOPMODEL wetness index (after Beven and Kirby 1979). All physical parameters including salt concentrations are averaged over wetness index categories. Tuteja *et al.* (2004) emphasise that many different landscape elements can have the same wetness index, which produces difficulties in modelling land use change scenarios. Another limitation of CATSALT is that it does not calculate ET; it uses spatially averaged pan evaporation as an input. Land use is not used as an input to calculate ET. Instead the influence of land use is introduced through land use efficiency indices (the ratio of long-term mean annual runoff under a given land use to that under pasture; Vaze *et al.* 2004). In addition, CATSALT does not adequately account for groundwater processes and therefore must be coupled to a hydrogeological model. For example, Tuteja *et al.* (2003) and Vaze *et al.* (2004) coupled CATSALT to FLOWTUBE. CATSALT has essentially been replaced by CLASS.

CATSALT has not been applied at national-scale as it requires some spatial datasets that are not available as Australia-wide coverage including depth to groundwater and salinity. Calibration of the model is necessary at catchment-scale using time-series stream flow data

(Tuteja *et al.* 2002). Stream flow data, particularly time-series data, is not available for many catchments in Australia.

6.1.5. TOPOG

The TOPOG framework is composed of a computational and hydrological unit called a 'kernel'. The kernel consists of suite analysis routines in which water balance computations are made (Vertessy *et al.* 1993). Water balance in this model includes daily transpiration and soil evaporation, as well as evaporation of water intercepted by the plant canopy. Surface runoff is calculated using the water balance equation. Runoff is then routed downslope along the flow strips and is also permitted to reinfiltrate when encountering an unsaturated element.

Topog_Yield is a spatially distributed model that operates by dividing small catchments into hydrological units, typically 20m x 20m, based on terrain analysis (Vertessy *et al.* 1993). Outputs can be aggregated to hydrologically sensible boundaries. The most sophisticated feature of Topog_Yield is the terrain analysis, which is used to create hydrologic units (typically 20 x 20 m) with associated topographic attributes and flow trajectories. Terrain analysis allows accurate routing of surface and subsurface flow through the landscape (Vertessy *et al.* 1993). Topog_Yield also simulates a range of ET processes: canopy interception (as the product of a canopy storage term and LAI), plant transpiration (using the Penman-Monteith equation) and soil evaporation (using the approach of Choudhury and Monteith 1988).

TOPOG has not been widely applied across Australia. The model is designed to be used in catchments less than 10km^2 and ideally for catchments less than 1km^2 (CSIRO Land and Water/CRC-CH 2002). Most input data (meteorological, soil, elevation and vegetation) are available for Australia, but only at a coarse resolution. Furthermore, the model is based on a network of small hydrological units; the division of Australia into small hydrologic units and catchments based on terrain analysis would be problematic and extremely time-consuming.

6.1.6. CLASS

CLASS is the most recently developed model. It was developed to overcome the limitations of CATSALT (Tuteja *et al.* 2004). CLASS accounts for the full range of processes that control the movement of water through the landscape including lagging, groundwater recharge, stream channel routing, throughflow, groundwater discharge and baseflow. CLASS includes pasture, crop and tree growth modules to simulate ET. Furthermore, CLASS attempts to address the problems associated with accessing input data by including a module, CLASS Spatial Analyst, to standardise and create input data. CLASS also includes a database of some input data and standard parameters.

In CLASS, runoff is calculated using the water balance equation. The water balance includes ET for three land use categories (crops, pasture and forest). The water balance is calculated for each grid cell on the land. Surface runoff generated at each grid cell is routed along the stream to the catchment outlet using the linear cascade model of Nash (1960) as in Kachroo and Liang (1992). Total generated groundwater discharge from landscape to the stream is routed using similar approach as the surface runoff (Tuteja *et al.* 2004).

As a spatially distributed model, CLASS produces output grids of a user-defined size. It is designed to operate at a range of scales from paddocks to large catchments (Tuteja *et al.* 2004). As the model routes water through the landscape, outputs can be aggregated to hydrologically sensible boundaries.

CLASS is a relatively new model and it has not been applied at the national-scale. According to Tuteja *et al.* (2004), CLASS is designed to operate in data poor environments and additional data can be incorporated into the model where available. One of the component models (Spatial Analyst) can be used to create appropriate datasets. However, a considerable amount of data is required to fully exploit the many component models. CLASS also requires a time-series of stream flow and stream salinity data for calibration. These data are not available for all catchments in Australia.

7. Conclusions

Water balance models play a vital role in Australian agriculture in terms of estimating water use, water allocation and the current water status. Most of these models are purpose-specific and suitable to be applied at a given spatial scale. As a general rule, it is known that large spatial scale modelling requires a simple model because lack of input data hampers the application of detailed models. However, as more continental scale data are becoming available, moving from simple models to more detailed models may be possible. For natural resource and water management purposes, research and policy agencies are focussing more on spatial modelling frameworks. A comprehensive review has been conducted for widely-used water balance models developed in Australia including models with spatial components, in which the model users can gather all necessary information to choose the right model for their purposes.

Water balance models can be categorised in terms of their treatment of the soil profile, ET, runoff and drainage. The degree of complexity of a model is based on the level of detail of these treatments. In this review, water balance models have been categorised based on their treatment of soil profile in terms of soil layers. With fixed soil layers, simple models with a bucketing approach are divided into single layer or multiple layers. Complex models with a continuous soil profile can either be one- or two-dimensional flow models. In line with the level of detail in processes employed in each model category, input data requirements vary considerably between categories. Single layer simple models require limited climate and soil data, whereas multiple layer simple models require additional information to describe vertically-structured soil layers, evaporation and root-related processes. One- or two-dimensional flow models are complex and employ detailed processes perhaps much more realistically than simple models. Thus, complex models need additional information, many of which are site-specific.

Most of these models, regardless of the category, have the capacity to be applied anywhere in Australia given no data constraints. Simple models with single layers often have the capacity to be applied at continental scale, while multi-layer simple models can be applied widely at regional or sub-regional scale. Most of the one-dimensional water flow models reviewed are point-based. However, some of the two-dimensional water flow models, such as CLASS and Topog_Yield, are spatial. They are ideally applied at catchment scale. Interest in modelling natural resources, including water balance assessments, has focused more on spatial variability, and models with spatial capacity are increasingly used in government policy development and implementation. Complex models, which normally hamper wide-range applications due to lack of specific data, should be encouraged to simplify their processes in order to be accommodated into spatial frameworks. Simple models should also be encouraged to improve their biophysical processes in line with new data sources to gain more accurate predictions.

The availability of input data can restrict the broad-scale application of many water balance models. Stream flow data are required for calibration of AWBM, CATSALT, TOPOG and CLASS, but are not available for all catchments within Australia. It is particularly difficult to access time-series stream flow data with a long historical record. BiosEquil and BiosEvolve do not require stream flow data for calibration and therefore may be more suited to national applications. All input datasets for BiosEquil are available for the Australian continent. As a steady-state model, BiosEquil only requires long-term mean annual and monthly climate data.

Water 2010 requires a spatially flexible model so that outputs can be summarised to areas of interest, including sub-catchments, catchments, river basins and management areas. AWBM and CATSALT are probably not sufficiently spatially flexible with respect to the goals of

Water 2010. AWBM is a lumped catchment model and CATSALT is semi-distributed. CATSALT calculates runoff for a catchment, which is then distributed based on topography and land use. Other modelling approaches examined are spatially distributed, including BiosEquil, BiosEvolve, AussieGRASS, TOPOG and CLASS. However, complex models such as CLASS and TOPOG have considerable data requirements and are computationally demanding. TOPOG, in particular, is very computationally demanding as it divides the landscape into small catchments and even smaller hydrologic units (typically 20m x 20m) based on terrain analysis.

Most of the models calculate runoff using a water balance equation, though the USDA Curve Number equation and empirical relationships are used by AussieGRASS and the AWBM. Flow routing procedures are present in CATSALT, TOPOG and CLASS. However, runoff outputs from pixel-based models without a standard routing technique, such as BiosEquil, can be summed based on catchment boundaries to provide a total runoff estimate at the catchment outlet. Only BiosEquil and AussieGRASS have been applied at the national-scale.

8. References

Abbs, F.T. (1984) Water balance modelling and its application to the Liverpool Plains, NSW. Proceedings of the Australian Society of Soil Science Workshop, Tamworth, 10-11 March 1984.

ABS (2000) Water Account for Australia, 1993-94 to 1996-97, catalogue number 4610.0, Australian Bureau of Statistics, Canberra.

ABS (2004) Agricultural Survey, Australian Bureau of Statistics: http://www.abs.gov.au/Ausstats/abs@.nsf/0/2c1d2617e23b5879ca256bd00027ed02?OpenDocument (accessed 12/09/05).

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1988) Crop evapotranspiration: Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. Water Resources, Development and Management Service, FAO, Rome.

ANCID (2005) Australian Irrigation Water Provider Benchmarking Data Report for 2003/2004: Key Irrigation Industry Statistics and Performance Indicators, Australian National Committee - International Commission on Irrigation and Drainage Incorporated.

AWRC (1987) 1985 Review of Australia's Water Resources and Water Use, Australian Water Resources Council, Canberra.

Barson, M.M., Randall, L.A. and Bordas, V. (2000) Land Cover Change in Australia, Results of the Bureau of Rural Sciences' and State agencies' state agencies project on the remote sensing of agricultural land cover change, Bureau of Rural Sciences and Agriculture, Forestry and Fisheries - Australia.

Beale, G.T.H., Beecham, R., Harris, K., O'Neill, D., Schroo, H., Tuteja, N.K. and Williams, R.M. (2000) Salinity Predictions for New South Wales Rivers within the Murray-Darling basin, Centre for Natural Resources, NSW Department of Land and Water Conservation.

Beven, K.J. and Kirkby, M.J. (1978) A physically-based variable contributing area model of basin hydrology. Hydrological Science Bulletin 24, 43-68.

Beverly, C.R. (1992) Background notes on the CSIRO Topog model. 1. Details of the numerical solution of the Richards equation in Topog_Yield. CSIRO Division of Water Resources, Canberra. Technical Memorandum 92/12, 51 pp.

Blackburn, G. and Mcleod, S. (1983) Salinity of atmospheric precipitation in the Murray-Darling drainage division, Australia. Australian Journal of Soil Research 21, 411-434.

Bleys, E. (2005) Personal Communication. Bureau of Rural Sciences Data Manager, Canberra.

BoM (2005) Australian Bureau of Meteorology: http://www.bom.gov.au (accessed 15/09/05).

Bond, W.J. (1994) Some practical considerations for model validation with field data. Agronomy Abstracts, Proceedings, Annual Meetings of the American Society of Agronomy, Seattle, U.S.A., November, 1984, American Society of Agronomy, Madison, 227.

Bond, W.J., Verburg, F., Smith, C.J., Ross, P.J. and Willett, I.R. (1993) Validation of analytical and numerical models of long-term movement of conservative tracers in unsaturated field soils. Agronomy Abstracts, Proceedings of Annual Meetings of the American Society of Agronomy, Cincinnati, USA, November, 1983, American Society of Agronomy, Madison, 201.

Boughton, W.C. (1995) An Australian water balance model for semi-arid watersheds. Journal of Soil and Water Conservation 50(5), 454-457.

Boughton, W. (2004) The Australian water balance model. Environmental Modelling and Software 19, 843-856.

Boughton, W. (2005) Catchment water balance modelling in Australia 1960-2004. Agricultural Water Management 71, 81-116.

Boughton, W.C. and Chiew, F. (2003) Calibrations of the AWBM for use on ungauged catchments. Technical Report 03/15. CRC Catchment Hydrology, Monash University, Melbourne, 37p.

Brinkley, T.R., Laughlin, G.P., Hutchinson, M.F. and Ranatunga, K. (In press) GROWEST PLUS – A tool for rapid assessment of seasonal growth for environmental planning and assessment, Environmental Modelling and Software.

Broadbridge P. and White I. (1988) Constant rate rainfall infiltration: A versatile nonlinear model—I. Analytical solution. Water Resources Research 24,145-154.

Brodie R.S. (2002) Putting groundwater on the map: A status report on hydrogeological mapping in Australia. Keynote Paper, Conf Proc. International Groundwater Conference, Balancing the Groundwater Budget, Darwin, Northern Territory, 12-17 May 2002.

Brodie, R.S., Hostetler, S. and Bleys, E. (2004) Report 3: Inventory of Water Data Standards, Protocols and Infrastructure, Australian Water Data Infrastructure Project, Report to the Executive Steering Committee for Australia's Water Resource Information (ESCAWRI), Bureau of Rural Sciences.

Bryan, B. and Marvanek, S. (2004) Quantifying and valuing land use change for Integrated Catchment Management evaluation in the Murray-Darling Basin 1996/97 – 2000/01, Stage 2 Report to the Murray-Darling Basin Commission, CSIRO Land and Water Client Report.

Burnash, R. J. (1985) The Sacramento Watershed Model, Hydrologic Modelling for Flood Hazards Planning and Management, University of Colorado at Denver, California-Nevada River Forecast Center, National Weather Service, Sacramento, CA.

Burnash, R.J.C., Ferral, R.L., McGuire, R.A. (1973). A Generalized Streamflow Simulation System - Conceptual Modelling for Digital Computers, U.S. Department of Commerce, National Weather Service and State of California, Department of Water Resources.

Carroll, C., Littleboy, M. and Halpin, M. (1992). Minimising soil erosion and runoff by maximising cropping opportunities. Mathematics and Computers in Simulation 33, 427-32.

Carter, J.O., Hall, W.B., Brook, K.D., McKeon, G.M., Day, K.A. and Paull, C.J. (2000) Aussie GRASS: Australian grassland and rangeland assessment by spatial simulation. In: Hammer, G., Nicholls, N. and Mitchell, C. (Eds) 'Applications of seasonal climate forecasting in agricultural and natural ecosystems - the Australian experience'. Kluwer Academic Press, Netherlands.

Carter, J.O., N.F. Flood, G.M. McKeon, A. Peacock, and Beswick, A. (1996) Development of a National Drought Alert Strategic Information System, Volume 4: Model framework, parameter derivation, model calibration, model validation, model outputs, web technology. Final Report on QPI 20 to Land and Water Resources Research and Development Corporation.

Charles-Edwards, D. A., Doley, D., and Rimmington, Gvb.M. (1986) Modelling Plant Growth and Development. Academic Press, Sydney.

Chiew , F.H.S., Kamaladasa, N.N., Malano, H.M. and McMahon. T.A. (1995) Penman-Monteith, FAO-24 reference crop evapotranspiration and class-A pan data in Australia, Agricultural Water Management 28, 9-21.

Clarkson, N.M., Clewett, J.F., Owens, D.T. and George, D.A. (2001) STREAMFLOW: a supplement to AUSTRALIAN RAINMAN to improve management of climatic impacts on water resources QI00087, Department of Primary Industries Queensland, Brisbane.

Clemente R.S., De Jong R., Hayhoe H.N., Reynolds W.D. and Hares M. (1994) Testing and comparison of three unsaturated soil water flow models. Agricultural Water Management 25, 135-152.

Cooper, R. (1994) The 1:250 000 Scale Groundwater Map Series of the Murray Basin. MDBC River Murray Mapping Conference, Albury.

Coram J.E., Dyson P.R., Houlder P.A. and Evans W.R. (2000) Australian groundwater flow systems contributing to dryland salinity. Bureau of Rural Sciences, Canberra.

CRC-CH (2000) Cooperative Research Centre for Catchment Hydrology. General approach to modelling and practical issues to model choice. Melbourne, Australia. www.toolkit.net.au/modelchoice (accessed 12/09/05).

CSIRO Land and Water and CRC-CH (2002) TOPOG Online, CSIRO Land and Water and Cooperative Research Centre for Catchment Hydrology: http://www.per.clw.csiro.au/topog/ (accessed 16/09/05).

Danaher, T.J., Carter, J.O., Brook, K.D., Peacock, A. and Dudgeon, G.S. (1992) Broad scale vegetation mapping using NOAA-AVHRR imagery. Proceedings of the Sixth Australasian Remote Sensing Conference, Wellington, New Zealand. Volume 3.

Dawes, W. and Hatton, T.J. (1993) TOPOG_IRM. 1. Model Description. CSIRO Division of Water Resources, Canberra. Technical Memorandum 93/5, 33 pp.

Dawes, W.R. and Short, D.L. (1993). The efficient numerical solution of differential equations for coupled water and solute dynamics: the WAVES model. CSIRO Division of Water Resources Technical Memorandum 93/19.

Dunlop, M. (2001) Australian Water Use Statistics, Report II of IV in a series on Australian water futures, Working Paper Series 01/03, CSIRO Sustainable Irrigated Systems, Land and Water Australia.

Dyer, R., Cafe, L. and Craig, A. (2001). The Aussie GRASS NT & Kimberley subproject Final Report. Queensland Department of Natural Resources and Mines, Brisbane.

Edraki, M., Smith, D., Humphreys, S., Khan, S., O'Connell, N. and Xevi, E. (2003) Validation of SWAGMAN Farm and SWAGMAN Destiny models. CSIRO Land and Water Technical Report 44/03, Griffith, Australia.

Erlanger, P.D., Poulton, D.C. and Weinmann, P.E. (1992) Development and application of an irrigation demand model based on crop factors. In: Conference on Engineering in Agriculture, Institution of Engineers Australian National Conference, Albury, 4-7 October 1992, 82/11, 283-288.

Evans, W.R. (1992) The Murray Basin Hydrogeological Map Series. AWWA Water Journal 19(16), 20-23.

Fitpatrick, E.A. and Nix, H.A. (1968). A model for simulating water balance regime in alternating fallow-crop systems. Agricultural Meteorology 6, 303-319.

Fitzpatrick, E.A. and Nix, H.A. (1970). The climatic factor in Australian ecology. In: Moore, R.M. (Ed) Australian Grasslands, Australian National University Press, 3-26.

Fitzpatrick, E.A., Slatyer, R.O. and Krishnan, A.I. (1967). Incidence and duration of periods of plant growth in central Australia as estimated from climate data. Agricultural Meteorology 4, 388-404.

Freebairn, D.M., Littleboy, M., Smith, G.D. and Coughlan, K.J. (1991) Optimising soil surface management in response to climatic risk. In: R.C. Muchow, R.C. and Bellamy, J.A. (Eds.), Climatic risk in crop production: Models and management in the semi-arid tropics and subtropics, CAB International, Wallingford, 283-305.

GA (2005) Geoscience Australia's Online Product Guide, Geoscience Australia, Australian Government: www.ga.gov.au/oracle/agsocat (accessed 13/09/05).

Gardner, E.A., Littleboy, M. and Beavers, P. (1995). Using a water balance model to assess the hydrological implications of on-site effluent disposal. 16th Federal Convention of the Australian Water and Waste Water Association, April 1985, Sydney, Australia.

Geeves, G.W., Cresswell, H.P., Murphy, B.W., Gessler, P.E., Chartres, C.J., Little, I.P. and Bowman, G.M. (1995) The physical, chemical and morphological properties of soils in the wheat-belt of southern NSW and northern Victoria. NSW Department of Conservation and Land Management and CSIRO Division of Soils Occasional Report.

Greacen, E.L. and Hignett, C.T. (1976) A water balance model and supply index for wheat in southern Australia. CSIRO Division of Soils Technical Paper No 27.

Green, T.R., Bates, B.C., Fleming, P.M. and Charles, S.P. (1997a). Simulated impacts of climate change on groundwater recharge in the subtropics of Queensland, Australia. In: Taniguchi, M. (Ed) Subsurface Hydrological Responses to Land Cover and Land Changes. Kluwer Academic. 197-204.

Green, T.R., Charles, S.P., Bates, B.C. and Fleming, P.M. (1997b). Simulated effects of climate change on groundwater recharge: Gnangara Mound, Western Australia. In: 24th Hydrology and Water Resources Symposium Proceedings, Auckalnd, New Zealand.

Grundy, M.J., Littleboy, M. and Heiner, I.J. (1992) Improving land evaluation: A case study of the use of an agricultural systems model with land resource survey. AURISA 1992 Conference, 25-27 November 1992, 281-280.

Habermehl, MA and Lau, J.E. (1987) Hydrogeology of the Great Artesian Basin Australia map at scale 1:2,500,000, Australian Geological Survey Organisation, Canberra.

Hall, W., Bruget, D., Carter, J., McKeon, G., Jyoteshna, Y.Y., Peacock, A., Hassett, R. and Brook, K. (2001) Australian grassland and rangeland assessment by spatial simulation (Aussie GRASS). QNR9 Final Report for the Climate Variability in Agriculture Program. Queensland Department of Natural Resources and Mines. http://www.longpaddock.qld.gov.au/AboutUs/Publications/ByType/Reports/AussieGRASSFinalReport/index.html

Hall, W., Day, K., Carter, J., Paull, C. and Bruget, D. (1997) Assessment of Australia's grasslands and rangelands by spatial simulation. MODSIM 97: International Congress on modelling and Simulation, Hobart, Tasmania, 8-11 December 1997.

Hatton, T.J., Dyce, P., Zhang, L., Dawes, W.R. (1995). WAVES - An Ecohydrological Model of the Surface Energy and Water Balance: Sensitivity Analysis. CSIRO Division of Water Resources Technical Memorandum 85.2.

Hatton, T.J., Walker, J., Dawes, W.R. and Dunin, F. (1992) Simulation of hydroecological responses to evaluated CO2 at the catchment scale. Australian Journal of Botany 40, 678-686.

Hayman, P.T. (1992) Using 100 years of Gunnedah rainfall data to investigate the role of pasture in reducing water table recharge. Proceedings Grassland Society of NSW, 7th Annual Conference, Tamworth 8-8 July 1992.

Hayman, P.T. and Kneipp, J. (1995) Opportunity cropping - A matter of definition. Proceedings, Making Catchment Management Happen, Gunnedah, 20 May - 1 June 1995. Liverpool Plains Land Management Committee.

Hingston, F.J. and Gailitis, V. (1976) The geographic variation of salt precipitated over Western Australia, Australian Journal of Soil Research, 14, 319-335.

Humphreys, E. Edraki, M. and Bethune, M. (2003) Deep drainage & crop water use for irrigated– a review of determinations in fields and lysimeters, CSIRO Land and Water, Technical Report 14/03.

Hutchinson, M.F. (1998a) Interpolation of rainfall data with thin plate smoothing splines: I two dimensional smoothing of data with short range correlation. Journal of Geographic Information and Decision Analysis 2(2), 152-167. http://publish.uwo.ca/~jmalczew/gida_4.htm (accessed 14/09/05).

Hutchinson, M.F. (1998b) Interpolation of rainfall data with thin plate smoothing splines: II analysis of topographic dependence. Journal of Geographic Information and Decision Analysis 2(2), 168-195. http://publish.uwo.ca/~jmalczew/gida_4.htm (accessed 8/09/05).

Hutchinson, M.F., McIntyre, S., Hobbs, R.J., Stein, J.L., Garnett, S. and Kinloch, J. (2005) Integrating a global agro-climate classification with bioregional boundaries in Australia. Global Ecology and Biogeography 14 (3), 197-212.

Hutchinson, M.F., Nix, H.A. and McMahon, J.P. (2002) GROWEST Version 2.0. Centre for Resource and Environmental Studies, Australian National University, Canberra. http://cres.anu.edu.au/outputs/growest.html (accessed 15/09/05).

Hutchinson, M.F., Stein, J.L. and Stein, J.A. (2000) Derivation of nested catchments and sub-catchments for the Australian continent. Centre for Resource and Environmental Studies, Australian National University. http://cres.anu.edu.au/outputs/audit/index.php (accessed 19/09/05).

Irannejad, P., Shao, Y., Findlater, P.A. (1997). The impacts of vegetation cover on the water balance budget: A model simulation. In: Munro, R.K and Leslie, L.M (Eds.) Climate prediction for agricultural and resource management. Australian Academy of Science Conference, 1987. Bureau of Resource Sciences. 319p.

Irannejad, P. and Shao, Y. (1996) The atmosphere-land surface interaction scheme (ALSIS): Description and validation. CANCES Technical Report No. 2, University of New South Wales, 28pp.

Irannejad, P. and Shao, Y. (1998) Description and validation of the atmosphere-land-surface interaction scheme (ALSIS) with HAPEX and Cabauw data, Global and Planetary Change 19, 87-114.

Jeffrey, S.J., Carter, J.O., Moodie, K.M and Beswick, A.R. (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software 16(4), 309-330.

Johnston, R.M., Barry, S.J., Bleys, E., Bui, E.N., Moran, C.J., Simon, D.A.P., Carlile, P., McKenzie, N.J., Henderson, B.L., Chapman, G., Imhoff, M., Maschmedt, D., Howe, D., Grose, C., Schoknecht, N., Powell, B. and Grundy, M. (2003) ASRIS: the database. Australian Journal of Soil Research 41, 1021-1036.

Jones, C.A. and Kiniry, J.R. (1986) CERES-Maize: A simulation model of maize growth and development. Texas A&M University Press, College Station, Texas.

Jones, D. Plummer, N., Rea, A. and Wang, W. (2004) The Generation and Delivery of Level-1 Historical Meteorological Data Sets, Australian Water Availability Project, Bureau of Meteorology.

Kachroo, R.K. (1992). River flow forecasting, Part 5. Applications of a conceptual model. Journal of Hydrology 133, 141-178.

Kachroo, R.K. and Liang, G.C. (1992) River flow forecasting. Part 2. Algebraic development of linear modelling techniques, Journal of Hydrology, 133, 17–40.

Kayaalp, A.S. (1999) Application of Rainfall and Isotope Data Chemistry to Hydro-Meteorological Modelling, PhD. Thesis, The Flinders University of South Australia.

Keig, G. and McAlpine, J.R. (1974) WATBAL: A computer system for the estimation and analysis of soil moisture regimes from simple climatic data. CSIRO Division of Land Use Research Technical Memorandum No 74/4.

Kellett, J.R., Ransley, T.R., Coram, J. and Jaycock, J. (2003) Groundwater Recharge in the Great Artesian Basin Intake Beds, Queensland. Final Report for the NHT Project #882713: Sustainable Groundwater Use in the GAB Intake Beds, Queensland. Bureau of Rural Sciences and Queensland Department of Natural Resources and Mines.

Keywood, M.D., Chivas, A.R., Fifield, L.K., Cresswell, R.G. and Ayers, G.P. (1997) The accession of chloride to the western half of the Australian continent, Australian Journal of Soil Research, 35(5), 1177-1190.

Khan, S., Xevi, E., O'Connell, N., Madden, J.C. and Zhou, F. (2000) A farm scale hydrologic economic optimisation model to manage waterlogging and salinity in irrigation areas. EMAC 2000 Conference Proceedings, September 2000, Melbourne.

Kitchin, M.B. and Barson, M.M. (1998) Monitoring Land Cover Change – specifications for the remote sensing of agricultural land cover change project 1990-1995, Bureau of Rural Sciences, Canberra.

Kumar, C.P and Purandara, B.K. (2003) Modelling of soil moisture movements in a watershed using SWIM, Agricultural Engineering Journal, 84, 47-51.

Lau, J.E., Commander, D.P. and Jacobson, G. (1987) Hydrogeology of Australia, Bureau of Mineral Resources, Geology and Geophysics, Bulletin 227, Australian Government Publishing Service, Canberra.

Lawrence, P.A. and Littleboy, M. (1990). Evaluating sustainable farming systems in Central Queensland, (Poster paper). 5th Australian Soil Conservation Conference, March 1990, Perth.

Lesslie, R., Barson, M., Bordas, V., Randall, L. and Ritman, K. (2003) Landuse Mapping at Catchment Scale: Information for Catchment Solutions, Science for Decision Makers, Bureau of Rural Sciences.

Littleboy, M., Cogle, A.L., Smith, G.D., Yule, D.F. and Rao, F-P.C. (1996a). Soil management and production of Alfisols in the semi-arid tropics. I. Modelling the effects of soil management on runoff and erosion. Australian Journal of Soil Research 34, 81-102.

Littleboy, M., Cogle, A.L., Smith, G.D., Yule, D.E and Rao, F-P.C. (1996b). Soil management and production of Alfisols in the semi-arid tropics. IV. Simulating decline in productivity caused by soil erosion. Australian Journal of Soil Research 34, 127-38.

Littleboy, M., Freebairn, D.M. and Hammer, G.L. (1992a). Impact of soil erosion on production in cropping systems, II. Simulation of production and erosion risks for a wheat cropping system. Australian Journal of Soil Research 30, 775-8.

Littleboy, M., Grundy,.M.J., Bryant, M.J., Gooding, D.O. and Carey, B.W. (1992b). Using spatial land resource data and computer simulation modelling to evaluate sustainability of wheat cropping for a portion of the eastern Darling Downs, Queensland. Mathematics and Computers in Simulation 33, 463-8.

Littleboy, M., Sachan, R.C., Smith, G.D.S., and Cogle, A.L. (1996c) Soil management and production of Alfisols in the semi-arid tropics II. Deriving relationships between residue cover and curve number from rainfall simulator data. Australian Journal of Soil Research 34, 103-111.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L. (1999). PERFECT: A computer simulation model of Productivity, Erosion, Runoff Functions to Evaluate Conservation Techniques. Queensland Department of Primary Industries, Bulletin QB88005, 119 pp.

Littleboy, M., Silburn, D.M., Freebairn, D.M. Woodruff, D.R., Hammer, G.L., Leslie, J.K. (1992c). Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. Australian Journal of Soil Research 30, 757-774.

Littleboy, M., Vertessy, R.A., Lawrence, P. (2003). An overview of modelling techniques and decision support systems and their application for managing salinity in Australia. 8th National Productive Use and Rehabilitation id Saline Land (RURSL) Conference. September, 2003. Yeppon, Queensland.

Lu H, Raupach MR and McVicar TR (2001) A robust model to separate remotely sensed vegetation indices into woody and non-woody cover and its large scale application using AVHRR NDVI time series. CSIRO Land and Water, Technical Report 35/01.

Lyons, W.F., Shao, Y., Munro, R.K., Hood, L.M. and Leslie, L.M. (1997). Soil moisture modelling and prediction over the Australian continent using the ALSIS land surface schema. In: Munro, R.K and Leslie, L.M (Eds.) Climate prediction for agricultural and resource management. Australian Academy of Science Conference, 1997. Bureau of Resource Sciences, 319p.

Manabe, S. (1969) Climate and ocean circulation: 1. The atmospheric circulation and the hydrology of the earth's surface. Monthly Weather Review 87, 738-774.

McAlpine, J.R. (1970). Estimating pasture growth periods and droughts from simple water balance models. In: 'Proceedings of the XI International Grassland Congress'. University of Queensland Press, St Lucia, Australia.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D. and Huth, N.I. (1995) ASPIM: an agricultural production system simulation model for operational research. Mathematics and Computers in Simulation 38, 225-231.

McCown, R.L, G.L. Hammer, J.N.G. Hargreaves, D.L. Holzworth, and D.M. Freebairn (1996) APSIM: A novel software system for model development, model testing and simulation in agricultural systems research. Agricultural Systems 50, 255-271.

McGaw, A.J.E., Milford, H.B, Chapman, G.A., Murphy, C.L., Edye, J.A., Macleod, A.P. and Simons, N.A. (2001) SALIS: Accessible Soil Information for better natural resource management. In: Proceedings of the Geospatial Information and Agriculture Symposium, Sydney 2001.

McKenzie, N.J., Jacquier, D.W., Ashton, L.J., and Cresswell, H.P. 2000. Estimation of Soil Properties Using the Atlas of Australian Soils. CSIRO Land andWater. Technical Report 11/00.

McKenzie, N.J., Jacquier, D., Isbell, R. and Brown, K. (2004) Australian Soils and Landscapes: An Illustrated Compendium, CSIRO Publishing, Collingwood, Australia.

McKeon, G.M., Rickert, K.G., Ash, A.J., Cooksley, D.G. and Scattini, W.J. (1982). Pasture production model. Proceedings of the Australian Society for Animal Production 14, 202-4.

MDBC (2005) Water Audit Monitoring Report 2003/04: Report of the Murray-Darling Basin Commission on the Cap on Diversions and Special Audit NSW Barwon-Darling/Lower Darling Cap Valley, Report of the Independent Audit Group, Murray Darling Basin Commission.

Metcalfe, A., Heneker, T.M., Lambert, M.F., Kuczera, G. and Itan, I. (2002) A comparison of models for catchment runoff. In: Proceedings of the 27th Hydrology and Water Resources Symposium, Institute of Engineers, Australia.

Meyer, W.S. (1988). Development of management strategies for minimising salinisation due to irrigation: Quantifying components of the water balance under irrigated crops. AWRAC Research Report 84/162.

Meyer, W. and Prathapar, P. (1992) SWAGMAN: Salt, water and groundwater management. Agricultural Systems & Information Technology 4(2), 23.

Meyer, W.S., Dugas, W.A., Barrs, H.D., Smith, R.C.G. and Fleetwood, R.J. (1990). Effects of soil type on soybean crop water use in weighing lysimeters 1. Evaporation. Irrigation Science 11, 68-75.

Meyer, W.S., Godwin, D.C., White, R.J.G. (1996). SWAGMAN Destiny. A tool to project productivity change due to salinity, waterlogging and irrigation management. Proc. 8th Australian Agronomy conf. Toowoomba, Qld. 425-428.

Meyer, W.S., Godwin, D.C., White, R.J.G. and Smith, D.J. (1995). NRMS Cohuna project. Detailed simulations of upward water movement using SWAGMAN Destiny. A Consultancy report submitted to Goulbourn Valley Waters.

Meyers, W.S., Smith, D.J. and Shell, G. (1998) Estimating Reference Evaporation and Crop Evapotranspiration from Weather Data and Crop Coefficients, an addendum to AWRAC Research Project 94/162: quantifying components of the water balance under irrigated crops, CSIRO Land and Water Technical Report 34/88.

Muncaster, S.H., Weinmann, P.E. and Mein, R.G. (1997). An application of continuos hydrologic modelling to design flood estimation. In: Proceedings of the 24th Hydrology and Water Resources Symposium, Auckland, New Zealand. Institute of Engineers, Canberra, Australia.

Murray, N., Perraud, J., Podger, G. and Argent, R. (2005) E2 Catchment Modelling Software: Component Models, Cooperative Research Centre for Catchment Hydrology: www.toolkit.net.au/e2 (accessed 13/09/05).

Nash, J. (1960) A unit hydrograph study with particular reference to British catchments. Proceedings of the Institute of Civil Engineers 17, 248-282.

NATMAP (1980) Atlas of Australian Resources. Vol. 3: Soils and Land Use. Division of Natural Mapping, Canberra.

NLWRA (2000a) Australian Water Resources Assessment 2000: surface water and groundwater- availability and quality, national Land and Water Resources Audit, Canberra.

NLWRA (2000b) Dryland Salinity Assessment 2000, National Land and Water Resources Audit.

NLWRA. (2001a). Australian Agriculture Assessment. A theme report for the National Land and Water Resources Audit, Canberra.

NLWRA (2001b) User Guide: Australian Irrigation Areas, Version 1a, National Land and Water Resources Audit, Canberra.

Northcote, K. H. with Beckmann, G. G., Bettenay, E., Churchward, H. M., Van Dijk, D. C., Dimmock, G. M., Hubble, G. D., Isbell, R. F., McArthur, W. M., Murtha, G. G., Nicolls, K. D., Paton, T. R., Thompson, C. H., Webb, A. A. and Wright, M. J. (1960-1968). Atlas of Australian Soils, Sheets 1 to 10. CSIRO Australia and Melbourne University Press, Melbourne.

O'Connell, P.E., Nash, J.E and Farrell, J.P. (1970). River flow forecasting through conceptual models. Part 2. The Brosna catchment at Ferbane. Journal of Hydrology 10, 317-328.

Owens, J.S., Silburn, D.M., McKeon, G.M., Carroll, C., Willcocks, J. and deVoil, R. (2003) Cover-runoff equations to improve simulation of runoff in pasture growth models. Australian Journal of Soil Research 41, 1467-1488.

Peel, M.C., Chiew, F.H.S., Western, A.W. and McMahon, T.A. (2000) Extension of Unimpaired Monthly Streamflow Data and Regionalisation of Parameter Values to Estimate Streamflow in Ungauged Catchments, National Land and Water Resources Audit, Theme-1 Water Availability: http://audit.ea.gov.au/ANRA/water/docs/national/Streamflow/Streamflow.pdf (accessed 19/09/05).

Philip, J.R. (1966) Plant water relations: Some physical aspects. Annual Review of Plant Physiology 17, 245-268.

Podger, G.M., Sharma, P.K., Black, D.C. (1984). An integrated water quality and quantity modelling suite. Proceedings of Environmental Flows Seminar, AWWA, Australia.

Prathapar, S.A., Bailey, M.A., Poulton, D.C. and Barrs, H.D. (1995) Evaluating watertable control options using a water balance and groundwater simulation model (SWAGSIM). Proceedings of the International Congress on Modelling and Simulation, Newcastle, NSW, Australia, 3, 19-23.

Prathapar, S.A., Meyer, W.S., Bailey, M.A. and Poulton, D.C. (1996) A water balance and groundwater simulation model: SWAGSIM. Environmental Software 11, 151-158.

Prathapar, S.A., Meyer, W.S., Jain, S. and van der Lelij, A. (1994) SWAGSIM A water balance and groundwater simulation model. CSIRO Division of Water Resources, Report No 84/3.

Prathapar, S.A., Meyer, W.S., Madden, J.C. and Alociljá, E. (1997). SWAGMAN Options: a hierarchical multicriteria framework to identify profitable land uses that minimize water table rise and salinisation. Applied Mathematics and Computation 83, 217-240.

Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C. and Strong, W.M. (1998) APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agricultural Systems 56 (1), 1-28.

QDNRM (2005) The Long Paddock - Climate Management Information for Rural Australia, Queensland Department of Natural Resources and Mines: http://www.longpaddock.qld.gov.au/index.html (accessed 22/09/05).

Raupach, M.R., Kirby, J.M., Barrett, D.J. and Briggs, P.R. (2001a) Balances of Water, Carbon, Nitrogen and Phosphorus in Australian Landscapes: (1) Project Description and Results, CSIRO Land and Water Technical Report 40/01.

Raupach, M.R., Kirby, J.M., Barrett, D.J., Briggs, P.R., Lu, H. and Zhang, L. (2001b) Balances of Water, Carbon, Nitrogen and Phosphorus in Australian Landscapes: (2) Model Formulation and Testing, CSIRO Land and Water Technical Report 41/01.

Ranatunga, K. and Murty, V.V.N. (1992) Modelling Water Deliveries for Tertiary Units in Large Irrigation Systems, Agricultural Water Management 21(3), 197-214.

Richards, R., Watson, I., Bean, J., Maconochie, J., Clipperton, S., Beeston, G., Green, D. and Hacker, R. (2001) AussieGRASS Southern Pastures Sub-project. Final Report for the Climate Variability in Agriculture Program, Department of Natural Resources and Mines, Queensland, DNRQ00172.

Rickert, K.G. and McKeon, G.M. (1982). Soil water balance model: WATSUP. Proceedings of the Australian Society for Animal Production 14, 198-200.

Ritchie, J.T. (1972). A model for predicting evaporation from a row crop with incomplete cover. Water Resources Research 8, 1204-13.

Robbins, C.W., Meyer, W.S., Prathaper, S.A., White, R.J.G. (1995) SWAGMAN-Whatif, an interactive computer program to teach salinity relationships in irrigated agriculture. Journal of Natural Resource and Life Sciences Education 24(2), 150-155.

Rose, C. W., Begg, J. E. Byrne, G. F., Torssell, B. W. R., and Goncz, J. H. (1972). A simulation model of growth-field environment relationships for Townsville stylo *(Stylosanthes humilis* H.B.K.). Agricultural. Meteorology 10, 161-83.

Ross, P. J. (1990a) Efficient numerical methods for infiltration using Richards' equation. Water Resources Research 26(2), 278-280.

Ross, P.J. (1990b). SWIM: a simulation model for water balance infiltration and movement: reference manual. CSIRO Division of Soils, 58p.

Salama, R., Hatton, T.J., Zhang, L. and Dawes, W.R. (1999). Predicting land use impacts on regional scale groundwater recharge and drainage. Journal of Environmental Quality 28, 446-460.

Scanlan, J.C., Pressland, A.J. and Myles, D.J. (1996) Runoff and soil movement on mid-slopes in north-east Queensland grazed woodlands. Rangeland Journal 18, 33-46.

Schreider, S., James, B., Seker, M. and Weinmann, P.E. (2003a) Sensitivity and error propagation analysis for the Goulburn Simulation Model built by REALM. Proceedings of International Congress on Modelling and Simulation (MODSIM2003) Townsville, 14-17 July 2003, 4, 1661-1666.

Schreider, S., Codner, G.P. and Salbe, I. (2003b) Sensitivity analysis of integrated system for water allocation modelling. Proceedings of 28th International Hydrology and Water Resources Symposium, Nov 2003, Wollongong, NSW, 3, 163-170.

Schwamberger, E. (1995) Assessment of two numerical models for simulating upflow from shallow water tables. CSIRO Division of Water Resources Technical Memorandum 95.5, 36.

Shao, Y., L. M. Leslie, R. K. Munro, P. Irannejad, W. F. Lyons, R. Morison, D. Short and M. S. Wood (1997) Soil Moisture Prediction over the Australian Continent. Meteorology and Atmospheric Physics 63(3-4), 195-215.

Sharifi, F. and Boyd, M.J. (1994) A comparison of the SFB and AWBM rainfall-runoff models. In: Proceedings of the Water Down Under Conference 3, Institute of Engineers Australia, 491-494.

Short, D.L., Dawes, W.R. and White, I. (1995). The practicability of using Richards' equation for general purpose soil-water dynamics models. Environment International 21, 723-730.

Slavich, P.G., Hatton, T.J. and Dawes, W.R. (1998). The canopy growth and transpiration model of WAVES: Technical description and evaluation. CSIRO Land and Water Technical Report, No 3/98.

Smith, D.J. and Humphreys, E. (2001) The benefits of winter crops after rice harvest Part 2: Models to predict what will happen in your situation. Farmers' Newsletter Large Area No. 157, 36-38.

Smith, D.J., Meyer, W.S. and Barrs, H.D. (1993). Effects of soil type on maize crop daily water use and capillary upflow in weighing lysimeters during 1989/90. CSIRO Division of Water Resources Technical Memorundum 93/20, 33p.

Smith, D.J., Meyer, W.S. and Barrs, H.D. (1996). Lucerne daily water use and capillary upflow using weighing lysimeters: Effects of soil type and groundwater salinity. CSIRO Division of Water Resources Technical Memorundum 96/6, 35p.

Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J. and Hallsworth, E.G. (1968) A Handbook of Australian Soils, RELLIM Technical Publications, Glenside, South Australia.

Stephens, D.J. (1995) Crop yield forecasting over large areas in Australia. PhD thesis, Murdoch University.

Stewart, J.B., Smart, R.V., Barry, S.C. and Veitch, S.M. (2001) 1986/87 Land Use of Australia - Final Report for Project BRR5, National Land and Water Resources Audit, Canberra.

Thackway, R., Donohue, R., & R, Smart. (2004). Integrated Regional Vegetation Information - A compilation of vegetation types for National Action Plan and Natural Heritage Trust regions. Bureau of Rural Sciences, Canberra.

Thomas, E.C., Gardner, E.A., Littleboy, M. and Shields, P.J. (1995). The cropping systems model PERFECT as a quantitative tool in land evaluation: An example for wheat cropping in the Maranoa area of Queensland. Australian Journal of Soil Research 33, 535-54.

Timsima, J., Godwin, D. and Connor, D.J. (2000) Watertable management for mungbean within rice-wheat cropping systems of Bangladesh: A simulation study. Proceedings of the International Symposium of Systems Approaches for Agricultural Development (SAAD3), 8-10 November, Lima, Peru.

Timsina, J. and Humphreys, E. (2003). Performance and application of CERES and SWAGMAN Destiny models for rice-wheat cropping systems in Asia and Australia: A review. CSIRO Land and Water Technical Report 16/03. CSIRO Land and Water, Griffith, NSW 2680, Australia. 57pp. http://www.clw.csiro.au/publications/technical2003/tr16-03.pdf (accessed 9/09/05).

Tupper, G., Crichton, J., Alcock, D. and Mavi, H. (2001) Australian Grassland and Rangeland Assessment by Spatial Simulation (AussieGRASS), High Rainfall Zone Temperate Pastures Sub-project (QNR9). Final Report for the Climate Variability in Agriculture Program. Department of Natural Resources and Mines, Queensland.

Tuteja, N.K., Beale, G., Gilmore, R., Beecham, R., Woolley, D. and Williams, M. (2000) Current and predicted future salt loads and stream salinity for the Murrumbidgee River from dryland salinisation processes, Proceedings of the 3rd International Hydrology and Water Resources Symposium, Perth, Australia.

Tuteja, N.K., Beale, G.T.H., Summerell, G. and Johnston, W.H. (2002) Development and Validation of the Catchment Scale Salt Balance Model - CATSALT (Version 1): A case study examination of a no land-use change scenarios and subsequent incremental reafforestation in the Kyeamba Valley, NSW, NSW Department of Land and Water Conservation.

Tuteja, N.K., Beale, G., Dawes, W., Vaze, J., Murphy, B., Barnett, P., Rancic, A., Evans, R., Geeves, G., Rassam, D.W., Miller, M. (2003) Predicting the effects of landuse change on water and salt balance - a case study of a catchment affected by dryland salinity in NSW, Australia. Journal of Hydrology 283(1-4), 67-80.

Tuteja, N. K., Vaze, J., Murphy, B. and Beale, G. T. B. (2004) CLASS – Catchment scale multiple-landuse atmosphere water balance and solute transport model. Technical Report. NSW DIPNR, Australia and CRC for Catchment Hydrology, Australia, CRC for Catchment Hydrology Technical Report 04/12. http://www.catchment.crc.org.au/pdfs/technical200412.pdf (accessed 12/09/05).

Vaze, J., Barnett, P., Beale, G., Dawes, W., Evans, R., Tuteja, N.K., Murphy, B., Geeves, G., Miller, M. (2004) Modelling the effects of landuse change on water and salt delivery from a catchment affected by dryland salinity, Hydrological Processes 19, 1613-1637.

Verburg, K. and Bond, W.J. (2003). Use of APSIM to simulate water balances of dryland farming systems in south eastern Australia. Technical Report 50/03. CSIRO Land and Water, Canberra, Australia. http://www.clw.csiro.au/publications/technical2003/tr50-03.pdf (accessed 15/09/05).

Verburg, K., Ross, P.J. and Bristow, K.L. (1996) SWIMv2.1 User Manual, Divisional Report 130, CSIRO Division of Soils, Australia.

Vertessy, R.A., Hatton, T.J., O'Shaughnessy, P.J. and Jayasuriya, M.D.A. (1993) Predicting water yield from a mountain ash forest catchment using a terrain analysis based catchment model. Journal of Hydrology 150, 665-700.

Vertessy, R.A., Hatton, T.J., Benyon, R.J. and Dawes, W.R.(1996) Long term growth and water balance predictions for a mountain ash (*E. regnans*) forest subject to clear felling and regeneration. Tree Physiology 16, 221-232.

Walker, G.R., Zhang, L., Ellis, T.W., Hatton, T.J. and Petheram, C. (2002) Estimating impacts of changed land use on recharge: review of modelling and other approaches appropriate for management of dryland salinity. Hydrogeology Journal 10, 68-80.

Wang, L. and Anderson, M.P. (1982). Introduction to Groundwater Modelling: Finite Difference and Finite Element Methods. W. H. Freeman and Company, San Francisco, 237p.

Wang, Q.J. McConachy, F.L.N., Chiew, F.H.S., James, R., de Hoedt, G.C. and Wright, W.J. (2001) Climatic Atlas of Australia: Maps of evapotranspiration, Cooperative Research Centre for Catchment Hydrology, University of Melbourne, Bureau of Meteorology.

Western, A. (2005) User Guide: Liza, Land Use for the Intensive Use Zone of Australia, Cooperative Centre for Catchment Hydrology: www.toolkit.net.au/liza (accessed 9/09/05).

Western, A. and McKenzie, N. (2004) User Guide: Soil Hydrological Properties of Australia, Cooperative Research Centre for Catchment Hydrology: www.toolkit.net.au/shpa (accessed 16/09/05).

White, D.H. and Walker, P.A. (2000) Insights into Agricultural Models. CSIRO Sustainable Ecosystems, Canberra, Australia.

Wigmosta, M.S.L. and Lettenmaier, D.P. (1994) A comparison of simplified methods for routine topographically driven subsurface flow. Water Resources Research 35(1), 255-264.

Williams, J.R. and La Seur, W.V. (1976) Water yield model using SCS curve numbers. Journal of Hydraulics Division, American Society of Civil Engineering 102, 1241-53.

Williams, J., Ross, P.J., and Bristow, K.L. (1991) Perspicacity, precision and pragmatism in modelling crop water supply. In: Muchow, R.C. and Bellamy, J.A. (Eds.) Climate Risk in Crop Production: Models and Management for the Semi-arid Tropics and Subtropics. CAB International, Wallingford, 73-86.

Williams, R.M., Wooley, D.R., Abel, R., Please, P.M., and Evans, W.R., (1994) Darling Basin Hydrogeological Map - Land & Water Management Issues, Water Down Under "94" Conference papers, Institute of Engineers, Australia, 193-198.

Wu, Q., Christen, E. and Enever, D. (1999) BASINMAN – A water balance model for farms with subsurface pipe drainage and an on-farm basin. CSIRO Land and Water Technical report 1/99.

Yee Yet, J.S. and Silburn, D.M. (2003) Deep drainage estimates under a range of land uses in the Queensland Murray-Darling Basin using water balance modelling. Department of Natural Resources and Mines, Coorparoo, Queensland, QNRM03021.

Zhang, L. and Dawes, W.R. (1998) WAVES: An Integrated Energy and Water Balance Model. CSIRO Land and Water Technical Report No. 31/98.

Zhang, L., Dawes, W. R. and Hatton, T. J. (1996) Modelling hydrologic processes using a biophysically based model - Application of WAVES to FIFE and HAPEX-MOBILHY, Journal of Hydrology 195, 330-352.

Zhang, P.G., Dawes, W.R., Slavich, P.G., Meyer, W.S., Thorburn, P.J., Smith, D.J. and Walker, G.R. (1999a) Growth and groundwater uptake responses of lucerne to changes in groundwater levels and salinity: lysimeter, isotope and modelling studies. Agricultural Water Management 39, 265-282.

Zhang, L., Dawes, W.R. and Walker, G.R. (1999b) Predicting the Effect of Vegetation Changes on Catchment Average Water Balance, Cooperative Research Centre for Catchment Hydrology, Technical Report 99/12.

Zhang, L., Hickel, K., Dawes, W.R., Chiew, F.H.S., Western, A.W. and Briggs, P.R. (2004) A rational function approach for estimating mean annual evaporation. Water Resources Research 40.

Zhang, L., Hickel, K. and Shao, Q. (in press) Water balance modelling over variable time scales. MODSIM Conference, December 2005, Melbourne.