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Review

Review of soil water models and their applications in Australia

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Abstract

Agriculture is the highest consumer of water resources in Australia. Soil water models play a vital role in agriculture in terms of estimating water use, water allocation and current water status at a given scale. This paper reviews widely-used soil water models developed in Australia over the last three to four decades that have been used to simulate soil water status at various temporal and spatial scales. These models are categorised in terms of their complexity. This paper provides an overview of soil water models and the basic modelling techniques employed by each model. Considerable emphasis is given to matching existing data availability with input data requirements for each model to identify the limitations of model application in terms of data availability. A comprehensive review of the application of soil water models is also given, supported by assessments of individual model performance. The limitations and assumptions made under various approaches to soil water modelling are subsequently examined. Research and policy agencies are focusing more and more on incorporating temporal models into spatial modelling frameworks for natural resources and water management purposes. These are consequently being used much more in the process of policy development. Complex models, whose wide-range application is often hampered by a lack of specific data, should have their processes simplified in order to be accommodated into spatial frameworks where appropriate. Biophysical processes within simple models should consider new data sources and understanding so as to gain more accurate predictions.

Keywords: Model review; Soil water modelling; Water balance; Simple models; Complex models; Data availability; Performances; Limitations; Applications

1. Introduction

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. Farmers have felt their water supplies squeezed recently by declining water allocations brought on by more-frequent droughts and less reliable effective rainfall. 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. In 2004, the Australian Government in association with State and Territory governments, with the exception of Western Australia and Tasmania, announced a comprehensive strategy, known as the National Water Initiative, for improving water management across the country. This new initiative noted the imperative of increasing the productivity and efficiency of water use and the health of river and groundwater systems in Australia. Many research and policy frameworks are emerging to increase the efficiency of water use in agriculture, in which soil water models play a vital role.

Most soil water models developed in Australia combine plant water use, soil water storage and water table fluctuations in varying degrees of complexity to predict current and future soil water storage and plant water availability. Although model choice should be made using a ‘‘horses for courses’’ approach (CRC Catchment Hydrology, 2000), it is sometimes confusing and difficult to choose the right soil water model for a specific purpose because of often subtle differences between many of these models in terms of their original purpose and how they were designed. It was consequently realised that

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a comprehensive review of widely-used soil water models developed in Australia would be valuable. Within this review, current and potential users of soil water models should be able to assess existing models in terms of their complexity, input data required to run the model, current state of input data availability, model performances under various conditions and their limitations, in particular with respect to soil and vegetation types and applications.

Models that relate runoff to rainfall are usually applied at catchment or sub-catchment scales and are known as catchment water balance models. Since a review of 13 catchment water balance models in Australia, has been completed elsewhere (Boughton, 2005), most of these models were not included in this study. However, some catchment-based models with an explicit soil water component are discussed.

Similarly, an overview of salinity models and modelling can be found in Littleboy et al. (2003) and consequently this review does not explicitly cover salinity-related models, although a couple of salinity models are included because of their significance in soil water modelling. Effects of climate change on water availability have been modelled by Hood et al. (2006) for key agricultural enterprises in Victoria, Australia. A considerable effort has also been made into modelling biophysical and economic aspects of Australian farming systems and landscapes by Hook (1997).

We have chosen widely-used soil water models developed in Australia over the last three to four decades in this review. While every effort has been made to provide a comprehensive review, we acknowledge that there may be work, in both published and unpublished forms, not accounted for in this review. For example, there are several soil water submodels developed for crop models (O'Leary and Connor, 1996; Moore et al., 1997; Meinke et al., 1998), which are beyond the scope of this paper.

2. Categorisation of soil water models

Physically-based or mechanistic models differ from empirically-based models in terms of degree of complexity, which is often determined by the specific purpose of the model development. In reality there is a continuum between these extremes, from totally mechanistic to completely empiric, with most models at least containing a degree of physical or biophysical logic (White et al., 1993). The more empirical models are often more accurate at local or regional scales, providing they have been extensively calibrated and validated using local data, whereas more generic models tend to be more reliable on average when applied across an extensive geographic area.

It therefore seemed appropriate to start by categorising soil water models in terms of their degree of complexity based on the treatment of the soil profile, in addition to the number of processes employed (Fig. 1). "Simple models" have a fixed number of soil layers and a tipping bucket approach to water inflows and outflows, while "complex models" seek to incorporate a continuous soil profile. 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. All the soil water models considered in this review are given in Table 1.

The major processes employed in soil water modelling are similar, but the level of detail in each component varies significantly. Table 2 identifies the method used by each model for estimating evapotranspiration losses from soils and plants and consideration of soil evaporation and canopy interception. Table 2 also identifies the method used to calculate surface runoff and consideration of subsurface runoff, drainage and infiltration processes.

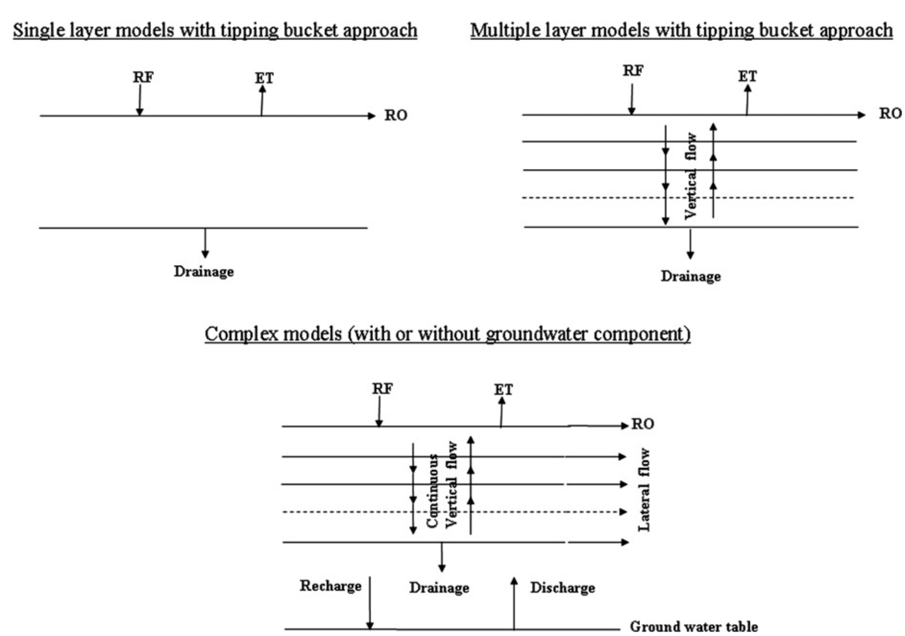

Fig. 1. Schematic diagram for basic processes employed by each category of water balance models identified in this review. RF, ET and RO refer to rainfall, evapotranspiration and runoff.

Table 1
Australian soil water models considered in this review

Model name	Explanation of name	Key reference
WATBAL	Water balance model	Fitzpatrick et al., 1967; Fitzpatrick and Nix, 1969; McAlpine, 1970; Keig and McAlpine, 1974
GROWEST	Growth estimation	Fitzpatrick and Nix, 1970; Hutchinson et al., 2002
PRIDE	Program for regional irrigation demand estimation	Erlanger et al., 1992
BiosEquil	Mass balances of water, carbon, nitrogen and potassium fluxes	Raupach et al., 2001a
AWBM	Australian water balance model	Boughton, 2004
IQQM	Integrated quality and quantity model	Podger et al., 1994
REALM	Resource allocation model	Schreider et al., 2003a,b; Perera et al., 2005
MSM-BIGMOD	Monthly simulation model for daily flow and salinity routing	Close et al., 2004
PERFECT	Productivity, erosion and runoff functions to evaluate conservation techniques	Littleboy et al., 1992b
SoilWat	Soil water model	Verburg, 1995; McCown et al., 1995
GRASP	Grass production	Rickert and McKeon, 1982; McKeon et al., 1982
BASINMAN	Water balance model for farms with subsurface pipe drainage and an on-farm basin	Wu et al., 1999
CATSALT		Tuteja et al., 2002
SWIM	Soil water infiltration and movement	Ross, 1990b
APSIM SWIM	Agricultural Production systems simulator—SWIM	Connolly et al., 2002
WAVES	Water atmosphere vegetation energy solute	Dawes and Short, 1993; Hatton et al., 1995
Topog_Yield	Terrain analysis-based hydrologic modelling package	Vertessy et al., 1993
ALSIS	Atmosphere-land-surface interaction scheme	Irannejad et al., 1997, Irannejad and Shao, 1998b
CLASS	Catchment scale multiple-land use atmosphere soil water and solute transport model	Tuteja et al., 2004
SWAGSIM	Soil water and groundwater simulation model	Prathapar et al., 1996
SWAGMAN	Soil water and groundwater management model	Meyer and Prathapar, 1992

The relative capabilities of existing soil water models and the credibility of their results are still an important concern because soil water dynamics is 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.

2.1. Simple models with tipping-bucket approach

In early versions of soil water models, the soil moisture is typically modelled as a simple tipping 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 tipping bucket that represents soil or the root zone of a plant or plant community is full, the excess precipitation leaves as surface runoff. Initial development of soil water models in this category assumed vertically and horizontally homogeneous soil and thus the entire soil or root zone is represented as a single soil layer. Models considered in the review for single-layer simple category are WATBAL, PRIDE, GROWEST, BiosEquil and AWBM (Table 1).

While the assumption of uniform soils may be reasonable for spatial models applied to relatively small areas, it is unlikely to hold over the Australian continent (Irannejad and Shao, 1998a), where duplex soils are the most common, only after sandy soils (NATMAP, 1980). O'Connell et al. (1970) developed a soil water 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. Greacen and Hignett (1976) developed a two-layer soil water balance model under wheat (CERES). Two layers were considered, broadly corresponding to the surface and sub-soil horizons, on which the growing root zone of the crop was imposed. Multiple-layer tipping bucket water balance models developed in the last two decades owe much to their precursor in CERES (Jones and Kiniry, 1986). 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. Multiple-layer models considered in this review are PERPECT, SoilWat, GRASP, BASINMAN and CATSALT.

Another type of model considered within this category is water resource allocation models such as IQQM, REALM and MSM-BIGMOD (Table 1). These models are used to transform rainfall (rainfall on bare ground plus snow cover outflow) into runoff and have been developed for improved management of water flow and associated resources.

2.2. Complex models

In complex soil water models, soil water movement is usually treated as continuous rather than as a series of cascades as in the simple tipping bucket approach. Models with continuous flow are treated as complex and have either one or two-dimensional water flows. They are based on fundamental equations for hydraulic and hydrodynamic behaviour and the movement of water and solute through porous media. Richards' equation (Richards, 1931) is the commonly accepted basis for detailed studies of vertical water movement (Ross, 1990a). Analytical solutions to Richards' equation are not

Table 2
Treatment of evaporation, runoff and drainage in soil water models

Model	Method of plant evaporation				Soil evaporation	Interception evaporation	Method of surface runoff calculation			Subsurface runoff	Drainage process	Infiltration process
	FAO	P or PM	PT	Other			WB	US CN	Other			
WATBAL				✓			✓					
GROWEST				✓			✓					
PRIDE	✓						✓			✓	✓	
BioEquil			✓		✓	✓				✓	✓	✓
PERFECT				✓	✓			✓			✓	✓
APSIM/SoilWat				✓	✓			✓			✓	✓
SAC-SMA							✓			✓	✓	
BASINMAN	✓				✓		✓			✓	✓	✓
CATSALT				✓			✓			✓	✓	✓
BioEvolve			✓		✓	✓				✓	✓	✓
IQQM							✓			✓	✓	
SWIM				✓	✓				✓	✓	✓	✓
APSIM SWIM				✓	✓				✓		✓	✓
WAVES		✓			✓	✓	✓			✓		✓
CLASS		✓			✓	✓	✓			✓	✓	✓
SWAGSIM	✓									✓	✓	
SWAGMAN	✓									✓	✓	
Topog_Yield		✓			✓	✓	✓			✓	✓	✓

FAO, FAO method for evapotranspiration (Doorenbos and Pruitt, 1977); P or PM, Penman or Penman–Monteith method (Monteith, 1965); PT, Priestley–Taylor method (Priestley and Taylor, 1972).

possible for dynamic field situations and therefore, most models focus on numerical solutions (finite-difference or finite-element methods) with increased computing power. Darcy's law is not applicable for unsaturated conditions, but Darcy's law can, and has been, adapted for unsaturated flow by coupling it with the Richards' equation (Broadbridge and White, 1988; Ross, 1990b; Kemachandra and Murty, 1992) assuming that hydraulic conductivity and diffusivity are functions of volumetric water content, not soil depth (Philip, 1966). Hatton et al. (1992) and Vertessy et al. (1993) implicitly stated that the soil 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).

Broadbridge and White (1988) developed an analytical soil water model by solving Richards' equation to describe the relationships between water potential, volumetric water content and hydraulic conductivity. The Broadbridge and White soil water 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). The Richards equation was also used for some specific purposes such as to model water flow into soil from surface or buried emitters (Cook et al., 2006). Models considered in this review for complex models are SWIM, APSIM SWIM, WAVES, Topog_Yield, ALSIS, CLASS and SWAGSIM/SWAGMAN.

3. Availability of input data

Soil water models require a range of meteorological, soil, stream flow, irrigation and land use information. These datasets are available at varying spatial and temporal resolutions for different regions of Australia. Consideration of all relevant datasets is beyond the scope of this review which focuses on spatially distributed datasets, particularly those available for the Australian continent.

Other reviews of Australian datasets are available. Brodie et al. (2004), for example, provide a comprehensive review of water data in Australia. However, they do not review all datasets relevant to soil water models including land use, vegetation, soils and irrigation. Data availability is also discussed in manuals for some soil water models (e.g. Littleboy et al., 1999 for PERFECT; Raupach et al., 2001a,b for BiosEquil and BiosEvolve).

3.1. Meteorological data

The two main sources of meteorological data in Australia are the Bureau of Meteorology (BoM) and the Queensland Department of Natural Resources and Water's SILO Patched-Point Dataset (SILO PPD). The BoM maintains a network of several thousand weather stations throughout Australia (Fig. 2). 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 1890 for rainfall. Many stations do not have a continuous record, which can cause significant problems for soil water modelling.

The SILO PPD is an attempt to overcome some of the problems associated with data from the BoM's weather stations. Missing records have been filled in using spatial interpolation to provide continuous daily records of climate variables, such

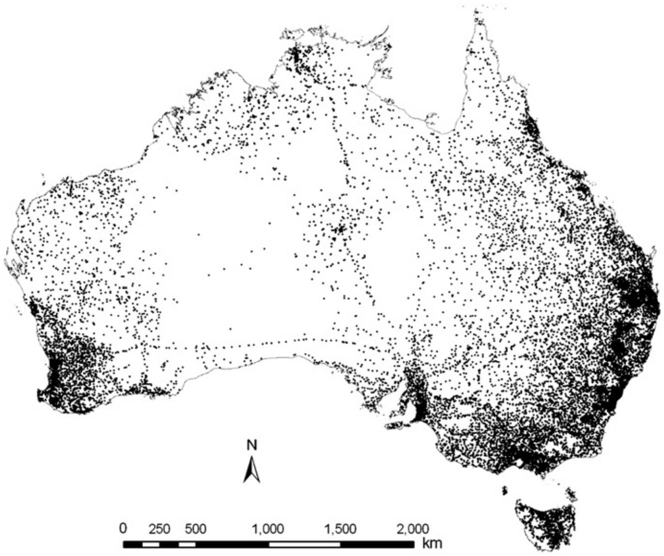

Fig. 2. Location of the BoM's weather stations.

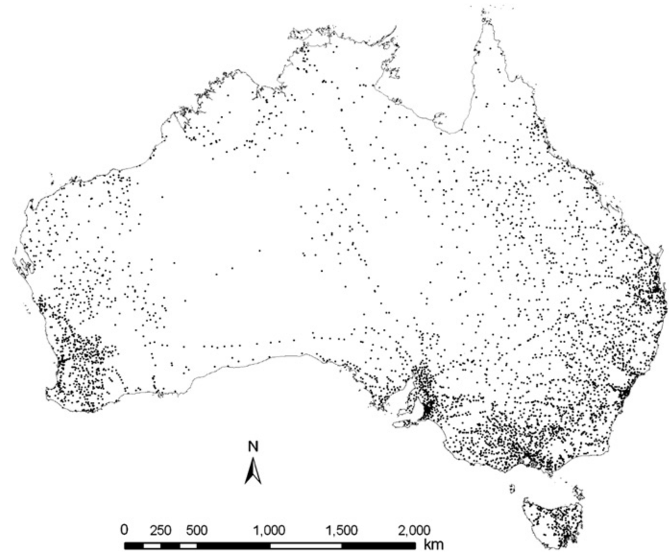

Fig. 3. Location of SILO PPD sites (after Jeffrey et al., 2001).

as rainfall, minimum and maximum temperature, solar radiation, vapour pressure and pan evaporation (Jeffrey et al., 2001). Data are available for 4600 sites across Australia (Fig. 3).

3.1.1. Rainfall

Rainfall is a required input for all soil water models. As the largest term in the water balance, rainfall is a significant source of error in soil water modelling (Boughton, 2005; Murray et al., 2005). Rainfall data are 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. 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.

The BoM produces daily and monthly rainfall grids at 0.05 degree ($\sim$5 km) and 0.25 degree ($\sim$25 km) resolution for the Australian continent (Table 4) (Jones et al., 2004).

In addition, daily and monthly rainfall grids are available as 0.05 degree ($\sim$5 km resolution) from 1889 to present through the SILO PPD (Table 6) (Jeffrey et al., 2001). These grids are designed for broad-scale analysis and may not be appropriate for some soil water models, particularly the point and farm-scale models, though datasets for specific locations can be generated by applying a data drill to the gridded surfaces.

Table 3
Selected climate variables available from the Bureau of Meteorology and QDNRM's SILO PPD (BoM 2005; Jeffrey et al., 2001)

Variable	Number of sites	
	BoM	SILO PPD
Dew point (humidity)	1533	–
Pan evaporation	585	4600
Rainfall	17,665	4600
Solar radiation	86	–
Temperature (min & max)	1817	4600
Wind speed	1817	–

3.1.2. Evaporation and evapotranspiration

Evapotranspiration is typically the second largest term in the water balance. Although the spatial and temporal variability of evapotranspiration is not as large as for rainfall, evapotranspiration is still a significant source of error in soil water modelling. It is difficult to quantify the errors associated with evapotranspiration because there are few observed datasets to validate modelled actual evapotranspiration. 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 evapotranspiration have been compiled by Humphreys et al. (2003) and Zhang et al. (1999b).

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

Grids of mean monthly and annual pan evaporation are available from the BoM. Pan evaporation is also part of the SILO PPD with daily pan evaporation is available as grids at a 0.05 degree resolution and for 4600 weather stations (Table 5). In addition, mean monthly and annual evapotranspiration (potential and actual) grids have been created by Raupach et al. (2001a) using the BiosEquil model (Table 5).

3.1.3. Temperature

Minimum and maximum daily temperatures are common inputs to soil water models that calculate evapotranspiration.

Table 4
Characteristics of spatial rainfall datasets for the Australian continent

	Bureau of Meteorology	Australian Water Availability Project	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	1889-present
Spatial interpolation	Barnes analysis	3-D smoothing spline (climatology) + Barnes analysis (anomaly field)	Ordinary kriging
Access	By request	By request	License required

Spatial temperature data can be sourced from the BoM and the SILO PPD (Table 6). Daily and monthly grids of minimum and maximum temperature are available from the BoM at a 0.05 degree (~5 km) and 0.25 degree (~25 km) resolution (Jones et al., 2004). Daily and monthly temperature grids from 1889 to present are also available at a 0.05 degree resolution from the SILO PPD (Jeffrey et al., 2001).

3.1.4. Other meteorological data

Some soil water models require other meteorological inputs, particularly to calculate evapotranspiration, including solar radiation, dew point temperature, relative humidity, vapour pressure and wind speed. These variables are measured at selected weather stations, and point-based data can be sourced from the BoM and the SILO PPD. Not all of these climate variables are available as spatial datasets (Table 7). Of these climate variables, only solar radiation and vapour pressure currently available in spatial datasets from the BoM. 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 (Jeffrey et al., 2001).

3.2. Soil and soil hydraulic properties

Soil data, and particularly soil hydraulic properties, are an important input to soil water models. Broad-scale soil data are available from three national datasets: the Digital Atlas of Australian Soils, the Australian Soils Resource Information System (ASRIS) and the CRC for Catchment Hydrology's Soil Hydrological Properties of Australia. The soil properties available from 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 with associated soil properties (Northcote et al., 1960–1968). 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 ASRIS is a more recent soils database, but the spatial coverage of some soil properties is limited to Australia's intensive agricultural zone (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).

The Cooperative Research Centre 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., 1960–1968) 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 soil water content (at field capacity and wilting point).

State and Territory government agencies also manage soil databases. Most databases contain a combination of soil mapping and point-based measurements of soil properties (McGaw et al., 2001). In addition, soil properties for reference soil

Table 5
Characteristics of spatial evaporation and evapotranspiration 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 Water
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, 2008	Raupach et al. (2001a)	Jeffrey et al. (2001)

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

	Bureau of Meteorology	SILO PPD
Custodian	Bureau of Meteorology	Queensland Department of Natural Resources and Water
Spatial resolution	0.25 degrees (from 1900 to present) or 0.05 degrees (from 1940 to present)	0.05 degrees (from 1889 to present)
Spatial extent	Australia	Australia
Temporal resolution	Daily and monthly	Daily and monthly
Method	Barnes analysis or 3-D smoothing spline	Anomaly-spline (1889–1956) and 3-D smoothing spline (1957–present)
Access	By request	License required

types can be found in the literature (e.g. Stace et al., 1968; Geeves et al., 1995; McKenzie et al., 2004).

3.3. Stream flow

Stream flow data are often required by water balance models 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 former Queensland Department of Primary Industries as part of the RAINMAN project (Clarkson et al., 2001). Data was only collected 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, the BoM maintains a network of more than 1900 stream gauges across Australia for flood monitoring. The BoM also maintains a database of stream gauges across Australia including gauges managed by other agencies. 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, 2000a) while 2005 stream flow was collected for Australian Water Resources 2005 (NWC, 2007). These datasets have been used to validate water balance models in the past (e.g. BiosEquil).

A high quality dataset of monthly stream flow from 1901 to 1988 was assembled by Peel et al. (2000) for 286 stream flow gauges mainly in eastern Australia (Fig. 4). However, the gauges are located in small catchments with areas between 50 km^2 and 2000 km^2, and are not representative of the entire continent.

Table 7
Summary of spatial climate datasets for the Australian continent

Variable	Bureau of Meteorology	SILO Patched Point Dataset	CSIRO Land and Water
Rainfall	✓	✓	
Pan evaporation	✓	✓	
Potential evapotranspiration	✓		✓
Temperature (min & max)	✓	✓	
Solar radiation	✓	✓	
Relative humidity	✓	✓	
Wind	✓		
Vapour pressure	✓	✓	
Vapour pressure deficit		✓	

3.4. Land use and vegetation

Land use and vegetation mapping is required by a number of distributed soil water models, such as BiosEquil, BiosEvolve and CLASS. Most continental-scale land use and vegetation maps are either produced by or collated by the Bureau of Rural Sciences (BRS) from data collected by State and Territory agencies. These datasets are summarised in Table 10.

National-scale land use maps produced by the BRS 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 1993, 1994, 1999, 1996, 2001 and 2002 (Stewart et al., 2001).

Catchment-scale land use mapping is compiled by the BRS (Lesslie et al., 2003) and has been completed for all States/Territories except New South Wales. National vegetation datasets, including the Integrated Vegetation Cover (Thackway et al., 2004) and Forests of Australia are also available from the BRS.

The broad-scale land use and vegetation maps may not be appropriate for local scale studies. Some soil water models require land use data at very fine spatial resolution. For example, some models require information about crop rotations in particular paddocks. Such information is not available on the national scale and could only be obtained for local areas based on field studies.

3.5. Irrigation data

Irrigation data is a common requirement for soil water models. These models often require information about the area of irrigated crops. A national-scale map of irrigated areas (“Australian Irrigation Areas, Version 1a”) was produced as part of the NLWRA (2001b). 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).

There is no comprehensive GIS database of irrigation infrastructure for all Australia (Kirk et al., 1995), but GIS datasets are held by various management authorities. National-scale

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	✓		✓
Thickness		✓	✓
Texture	✓	✓	
Bulk density		✓	
Erodibility		✓	
Permeability	✓		
Water holding capacity	✓	✓	✓
Saturated hydraulic conductivity		✓	✓
Soil water at field capacity			✓
Soil water at wilting point			✓
Other	Nutrient response, reaction trend	pH, carbon, phosphorus, nitrogen, clay, silt, sand	porosity
References	Northcote et al. (1960–1968)	Johnston et al. (2003)	Western and McKenzie (2004)

datasets are available for water storages, although only large, off-farm water storages are included in these datasets. The "Major water resources infrastructure" dataset was also created as part of the NLWRA (2000a). It contains the location and capacity of 1237 water storages from across Australia (NLWRA, 2000a). Similarly, a national register of around 500 dams is maintained by the Australian National Committee on Large Dams Incorporated. It contains information about dam location, volume, purpose and irrigation area (ANCOLD, 2008).

Current and historical dam levels are monitored by water authorities, such as Sun Water in Queensland and Water Corporation in Western Australia. The availability of this data has been reviewed by Brodie et al. (2004). Information about irrigation applications can be obtained from a number of sources at varying spatial scales for selected years, such as Australian National Committee on Irrigation and Drainage (ANCID, 2003, 2004, 2005).

3.6. Hydrogeology

Hydrogeological data is needed for many complex soil water 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 reviews 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 and Lau, 1997), the "Hydrogeology of the Darling Basin" (Williams et al., 1994) and the "Hydrogeology of the Murray Basin" (Evans, 1992; Cooper, 1994). In addition, other hydrogeological maps have been developed for specific purposes including salinity (NLWRA, 2000b) and groundwater flow systems (Coram et al., 2000) maps.

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, including bore

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

Database	State	Agency	Gauges	Access
–	ACT	Department of Primary and Municipal Services	68	By request: http://www.tams.act.gov.au/live/environment
NSW Water Information	NSW	Department of Natural Resources	1700	Online: http://www.waterinfo.nsw.gov.au/
–	NT	Department of Natural Resources, Environment and the Arts	160	Online: http://nt.gov.au/nreta/water/surface/data.html
WaterShed	QLD	Department of Natural Resources and Water	5000	Online: http://www.nrm.qld.gov.au/watershed/index.html
South Australian Surface Water Archive	SA	Department of Water, Land and Biodiversity Conservation	1035	Online: http://e-nrims.dwlbc.sa.gov.au/swa/map.cfm
Water Information System of Tasmania	TAS	Department of Primary Industries and Water	17,000	Online: http://water.dpiw.tas.gov.au/wist/ui
Water Resources Data Warehouse	VIC	Department of Sustainability and Environment	80,000	Online: http://www.vicwaterdata.net/vicwaterdata/home.aspx
Water Information System	WA	Department of Water	121,980[a]	By request: http://kumina.water.wa.gov.au/waterinformation/wric/wric.asp

[a] Water information database includes surface water, groundwater and meteorological sites.

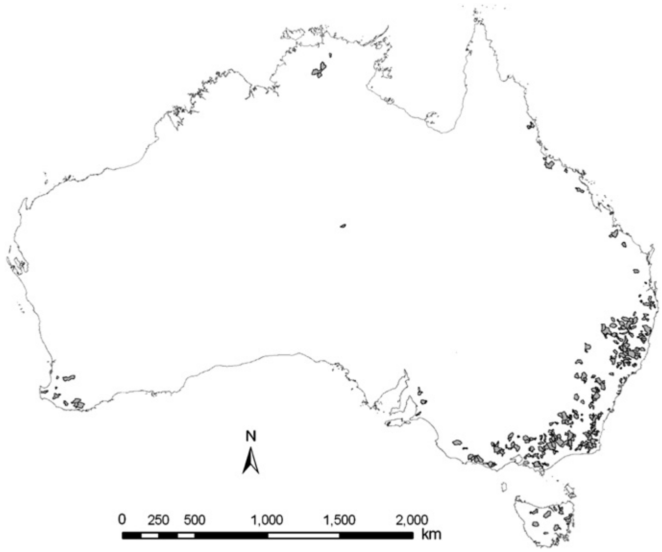

Fig. 4. The catchment boundaries for the stream flow gauges used in Peel et al. (2000).

location, groundwater level, aquifer lithology and groundwater salinity. Groundwater data was also collected as part of the NLWRA (2000a) and Australian Water Resources 2005 (NWC, 2007).

3.7. Water quality

In terms of water quality, salinity is the most common data requirement for soil water 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. Groundwater salinity contours are presented on hydrogeological maps including the "Hydrogeology of the Murray Basin" (Evans, 1992; Cooper, 1994) and the "Hydrogeology of the Great Artesian Basin" (Habermehl and Lau, 1997).

3.8. Agronomy

A wide range of agronomic information is required by soil water models. Only generic agronomy information can be obtained for the Australian continent. Specific, farm- and paddock-scale information is only available through field studies. Very general agronomic information can be obtained from land use maps (refer to Section 3.4). However, land use maps only represent the dominant land use for a particular year; they do not show crop rotations within a given year. The

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, 1994, 1997, 1999, 2001, 2002	1:2,500,000	Bureau of Rural Sciences: http://adl.brs.gov.au/mapserv/landuse/	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://adl.brs.gov.au/mapserv/landuse/	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, 2001a
Land Cover for the Intensive Use Zone of Australia	The University of Melbourne	Intensive use zone of Australia	1990, 1995	1 km 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	25, 100 and 250 m grid cells	Australian National Resource Data Library: http://adl.brs.gov.au/anrdl/php/basic_search.php	Kitchin and Barson, 1998; Barson et al., 2000
Integrated Vegetation Cover	Bureau of Rural Sciences	Australia	1996–2003	100 m grid cells	Australian National Resource Data Library: http://adl.brs.gov.au/anrdl/php/basic_search.php	Thackway et al., 2004
Forests of Australia	National Forest Inventory	Australia	2003	250 m grid cells	Australian National Resource Data Library: http://adl.brs.gov.au/anrdl/php/basic_search.php	
National Vegetation Information System (NVIS)	Australian Government Department of Environment, Water, Heritage and the Arts	Australia (incomplete)	Current and pre-European	100 m grid cells	National Vegetation Information System: http://www.environment.gov.au/erin/nvis/mvg/index.html	
National Plantation Inventory (NPI)	Bureau of Rural Sciences	Australia	Current	250 m grid cells	Bureau of Rural Sciences: http://www.daff.gov.au/brs	
Leaf Area Index (LAI)	CSIRO Land and Water	Australia	Mean annual and monthly (1991–94)	0.05 degree (~5 km) grid cells	Australian National Resource Data Library: http://adl.brs.gov.au/anrdl/php/basic_search.php	Lu et al., 2001

ABS collects a range of agricultural statistics including the area, production and value of crops, livestock numbers, livestock products, land management and irrigation (ABS, 2004).

Generic information about crops and crop management in Australia, such as planting date and fallow period, can be obtained from field surveys as well as from the literature (e.g. Cornish and Pratley, 1987; Jessop and Wright, 1991; Anderson and Garlinge, 2000). State and Territory agencies also provide regional agronomic information. The Food and Agriculture Organisation of the United Nations (FAO) is the traditional reference for crop coefficients (Allen et al., 1998) while Meyer et al. (1999) provide a comprehensive Australian dataset of crop coefficients for wheat, soybean, maize, lucerne, rice and pasture.

3.9. Topography and hydrological mapping

Digital Elevation Models (DEMs) are a common requirement for distributed water balance models, such as CLASS and Topog_Yield. National DEMs are available at a 90 m resolution from the NASA Shuttle Radar Topography Mission (SRTM) and at a 9 second (~250 m) resolution from Geoscience 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 provide catchment boundaries including river basins, which divides Australia into 12 drainage divisions, 77 water regions, and 245 river basins. Boundaries for surface water and groundwater management units are also available from Geoscience Australia. A hierarchy of nested catchment boundaries is available from the Centre for Resource and Environmental Studies (CRES) at the Australian National University. Four levels of catchments and sub-catchments 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. Geoscience Australia 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. 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.

3.10. Other data

Some soil water 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).

4. Model performance and limitations

Most of the models discussed are purpose-specific and suitable for application at a given spatial scale. Keeping this in mind, data requirements and model performances are discussed in this section. The data requirements for both simple and complex models are summarised in Tables 11 and 12, respectively. The limitations and assumptions made under various approaches to water balance modelling are also examined. A summary of water balance model applications is given in Table 13.

4.1. Simple models with tipping-bucket approach

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. As a result, single-layer simple models typically have modest data requirements. By comparison, simple models with multiple soil layers are able to incorporate the vertical heterogeneity of soil, but demand additional data.

4.1.1. WATBAL

One of the early single layer models developed in Australia is WATBAL in which the moisture index proposed by Fitzpatrick and Nix (1970) is calculated. The WATBAL model has a three reservoir (plant interception, soil and groundwater) water balance model to estimate groundwater recharge. It uses readily-available rainfall and potential evapotranspiration data and a single variable that defines the maximum soil water storage as input data.

The improved version of WATBAL is still in use in the regional wheat yield forecasting model, STIN (Stephens, 1995). WATBAL is also extensively used in the northern pastoral region to derive soil water balance and plant growth.

4.1.2. GROWEST

GROWEST 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, the GROWEST model is still used in climate impact studies and agro-climatological classifications (Hutchinson et al., 2005). A spatial version of GROWEST (GROWEST PLUS) has been developed by Laughlin et al. (2006) for the assessment of Exceptional Circumstances drought applications. GROWEST and GROWEST PLUS 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.

4.1.3. PRIDE

The PRIDE model 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

Table 11
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						✓			✓			
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)						✓						
Crop type			✓			✓						
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		✓				✓	✓

requirements. In addition to the features found in WATBAL and GROWEST, PRIDE calculates irrigation requirements and evapotranspiration using the FAO method (Doorenbos and Pruitt, 1977), which in turn requires some plant-specific parameters such as crop coefficients and potential evapotranspiration. Although crop coefficients vary from region to region (Meyer et al., 1999), generic values have often been used (Allen et al., 1998).

There are no climate data constraints for PRIDE as point and spatial rainfall and pan evaporation data are readily available from both SILO PPD and BoM. Long-term monthly mean potential evapotranspiration is also available to estimate actual evapotranspiration. Canal capacity constraints required by PRIDE are specific to irrigation system and are normally available from irrigation authorities. PRIDE performs well under conditions where the crop water requirements and farmer irrigation practices are well known (White and Walker, 2000). It is suitable for the prediction of irrigation demands under changing land use scenarios. PRIDE can also be integrated with other water resource allocation models such as REALM.

4.1.4. BiosEquil

A statistical steady-state landscape dynamics model, BiosEquil, uses a single water store. In an attempt to increase model performance and versatility, a time-dependent version for BiosEquil (BiosEvolve) was developed from the steady-state model. The water store in BiosEvolve is divided into two unsaturated soil reservoirs. Both models use the Priestly-Taylor equation to calculate potential evapotranspiration and the Budyko (1974) equation to calculate actual evapotranspiration (after Zhang et al., 1999b). The BiosEquil model uses land use as an input and therefore could be used to model the effects of land use change.

BiosEquil and BiosEvolve contain more processes than WATBAL, GROWEST and PRIDE such as soil evaporation, interception evaporation, subsurface runoff and subsurface drainage (Raupach et al., 2001a,b). As a result, BiosEquil requires more parameters and climatic variables, most of which are either available or are in the process of being developed spatially. All input datasets for BiosEquil are readily available on a national scale. The model has been already applied on the national scale as part of NLWRA, although the outputs were not rigorously validated. BiosEvolve has not been applied on a national scale. BiosEvolve has additional requirements for meteorological and soil data, which are available through SILO PPD and ASRIS respectively. In addition to water balance, BiosEquil estimates carbon, nitrogen, phosphorus as well as net primary productivity of the Australian landscape. As part of the NLRWA, the outputs from BiosEquil were summarised to the 245 River Basins and 12 Drainage Divisions (Raupach et al., 2001a).

4.1.5. AWBM

AWBM is a catchment-based water balance model that uses a simple water balance approach to estimate runoff from daily or hourly precipitation and mean monthly areal potential evapotranspiration (Boughton, 2004). It also uses a pattern

Table 12
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								✓
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						✓	✓	
Land use and vegetation								
Land use					✓	✓		
Land cover								
Vegetation type	✓			✓				✓
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							✓	
Economic component							✓	
Digital Elevation Model					✓			✓
Nutrient/solute concentration	✓	✓						

Table 13
Summary of model applications in Australia

Model	Enterprise	Location/Industry	References
WATBAL	Simple water balance calculations	In regional wheat yield forecasting model (STIN)	Stephens, 1995
PRIDE	District irrigation water demand	Goulburn Murray water	Erlanger et al., 1992
GROWEST, GROWEST Plus	EC applications	BRS	Hutchinson et al., 2002; Laughlin et al., 2006
BiosEquil	Long-term averages of H_2O, C, N and P	National Land and Water Resources Audit	Raupach et al., 2001a
	National water balance study—Water2010	BRS	
PERFECT	Erosion-productivity relationships	For Wheat; For Alfisols in the semi-arid zone	Littleboy et al., 1992a, 1996b
	Effects of cropping systems on runoff, erosion and yield	Gunnedah and Liverpool plains, NSW	Carroll et al., 1992, Hayman, 1992, Abbs, 1994, Hayman and Kneipp, 1995
	Surface management options and land evaluation	Semi-arid tropics/subtropics For Alfisols in the semi-arid	Freebairn et al., 1991, Grundy et al., 1992, Littleboy et al., 1995, Littleboy et al., 1996a, Thomas et al., 1995
	Effects of crop and pasture rotations on runoff, erosion and drainage	Central Queensland	Lawrence and Littleboy, 1990
IQQM	Impacts of water resource management policies or policy changes	Murrumbidgee, Lachlan, Macquarie, Namoi, Gwydir, Barwon Darling, Border Rivers, Moonie, Paroo, Condamine-Balonne	MDBC, 2005
	Land use and climate change	Macquarie river catchment	Herron et al., 2002
REALM	Water yield, allocation and security of supplies	Some parts of Victoria, South Australia and Western Australia	Schreider et al., 2003a,b, MDBC, 2005
MSM-BIGMOD	Flow and salinity processes	Murray river	MDBC, 2005
CATSALT	Land-use change and climate variability on the water and salt balance at a catchment scale	Boorowa River	Vaze et al., 2004
		Mandagery Creek	Tuteja et al., 2003
		Murray	Beale et al., 2000
		Kyeamba Valley	Tuteja et al., 2002
		Murrumbidgee	Tuteja et al., 2000
	NSW Salinity Strategy and the Murray Darling Basin Salinity Audit	DLWC NSW	
BASINMAN	T to control water logging	Murrumbidgee irrigation area, NSW	Wu et al., 1999
SWIMv1	Prediction of contaminant leaching from land irrigated with uranium mine waste water	Alligator Rivers Region	Ross, 1990b; Bond et al., 1993; Bond, 1994
	Estimation of upflow from static water tables	Murrumbidgee Irrigation Area, NSW	Schwamberger, 1995
SWIMv2	Salt and nitrate leaching to the groundwater following effluent irrigation	Wagga Wagga	Bond et al., 1997
WAVES	Recharge under current and proposed land uses over a range of climatic and geologic zones	Natural Resources Management Strategy for Victorian State agencies	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
APSIM SWIM	Crop growth in terms of water balance dynamics	Widely used in several cropping systems	McCown et al., 1996; Stewart et al., 2003
ALSIS	Land surface parameterisation scheme	Model development	Irannejad and Shao, 1998a
	Soil moisture modelling and prediction	Australian continent (UNSW and BRS)	Lyons et al., 1997; Irannejad and Shao, 1998b
	Impacts of vegetation cover on the water balance budget	Goodlands region, WA	Irannejad et al., 1997

(continued on next page)

Table 13 (*continued*)

Model	Enterprise	Location/Industry	References
CLASS	Effects of land use and climate variability on catchments	Landscape Strategy for the Snowy Monaro region, MDBC Salinity Audit 2004/2005	Tuteja et al., 2004
	Catchment scale land use effects in the Simmons Creek catchment	Billabong Murray, GRDC funded CSIRO, DPI NSW and DIPNR project	
SWAGSIM	Management options for shallow water tables	Murrumbidgee Irrigation Area, NSW	Meyer and Prathapar, 1992
SWAGMAN Options	Non-rice land uses with induce discharge from shallow water tables	Camarooka Project area, NSW	Prathapar et al., 1997
	Impact of rice growing on water table	Murrumbidgee Irrigation Area, NSW	Smith and Humphreys, 2001
	Farm scale salt and water management	Murrumbidgee Irrigation Area, NSW	Khan et al., 2003
SWAGMAN Destiny	Sustainable rice farming	Murrumbidgee Irrigation Area, NSW	Khan et al., 2001

of surface storage capacities and partial areas within a catchment that allow the runoff generating part of AWBM to be represented by a single runoff characteristic (Boughton and Chiew, 2003). AWBM has minimal data requirements (daily rainfall and actual evapotranspiration). A time-series of daily stream flow is required for calibration. A self-calibrating version of the model for these constants has performed well for many Australian catchments (Boughton, 2004).

AWBM is adapted for use on both gauged and ungauged catchments (Boughton, 2004). 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. 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 runoff at the catchment outlet.

The main limitation of AWBM is that it does not calculate evapotranspiration; actual evapotranspiration must be entered into the model. As a lumped model, inputs and outputs are spatially averaged across the catchment (Boughton, 2004). AWBM does account for the spatial variability of surface storage capacity by introducing three partial areas and corresponding capacities. In the runoff estimation project of the NLWRA, AWBM was calibrated for 221 catchments in Australia (Boughton and Chiew, 2003). However, they advised that this version of the model is not suitable for small, agricultural catchments.

4.1.6. PERFECT

Based in part on the CERES model, PERFECT 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 in the sub-tropics of Australia. This paddock scale model has multiple soil layers and is performed on a daily time-step. The Williams–Ritchie (Ritchie, 1972; Williams and La Seur, 1976) water balance model is used in PERFECT. Transpiration is represented as a function of potential evaporation, leaf area and soil moisture. Surface runoff is calculated as a function of rainfall, soil water deficit, surface roughness, surface residue and crop cover.

PERFECT has been validated widely (Table 13). One of the limitations in PERFECT is that partial area runoff processes and subsurface flow are not considered. Similar to PRIDE, there are no climate data constraints for PERFECT. Also, collecting site-specific soil properties such as soil thickness, bulk density and soil water characteristics is not easy, although the ASRIS and other soil datasets can provide such soil properties for Australia. 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.

4.1.7. SoilWat

The soil water component (SoilWat) of the APSIM modelling shell is the result of re-engineering of the CERES water balance model and introducing alternative infiltration and runoff routines from PERFECT. Further enhancements for SoilWat have also occurred beyond CERES and PERFECT (Probert et al., 1998). 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. Data constraints described in PERFECT, such as irrigation and soil data, often apply for SoilWat as well. APSIM was found to reproduce closely the water balance measurements from several sites in the Australian cereal belt. APSIM is a valuable tool for evaluating the impact of changes to cropping systems and agronomic practices on the water balance of dryland regions (Verburg and Bond, 2003).

4.1.8. 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 combines the "growth index" approach (Fitzpatrick and Nix, 1970), "water use" approach (Rose et al., 1972) and "radiation use efficiency" approach (Charles-Edwards et al., 1986) to model plant growth (Tupper et al., 2001). This model has a four-layer soil water budget. GRASP has been used in AussieGRASS as its plant growth and water balance module (Carter et al., 2000). In GRASP, runoff is calculated using two methods: the Scanlan method and a modified USDA Curve Number approach. The original Scanlan method is an empirical function of groundcover, daily rainfall, rainfall intensity and soil moisture deficit (Scanlan et al., 1996). More recently a modified USDA Curve Number approach has been incorporated into GRASP (Owens et al., 2003).

AussieGRASS requires spatial meteorological, soil, vegetation and stock management data. The daily grids of rainfall, minimum and maximum temperature, pan evaporation, solar radiation and vapour pressure deficit required by AussieGRASS (Carter et al., 2000) are available through SILO PPD. Soil type and associated parameters are required for four soil layers including layer thickness, bulk density and soil water content (at air dry state, wilting point and field capacity). The upper limit to daily soil evaporation must also be specified. Some of these data are available through various sources (Table 8).

The AussieGRASS framework and the underlying GRASP model are designed to operate in rangeland environments (Carter et al., 1996) and have been used for southern temperate pastures (Tupper et al., 2001). As the model does not calculate crop evapotranspiration, AussieGRASS may have limited application in areas dominated by cropping. Furthermore, AussieGRASS does not use the water balance equation to calculate runoff. However, the advantage of having empirically-developed relationships in GRASP is that the model requires relatively few parameters to calibrate.

4.1.9. BASINMAN

Wu et al. (1999) developed the BASINMAN model with the aim of increasing the understanding of hydraulic relationships between farmed areas and on-farm basins, which can be used to optimise basin design, minimise basin area and control water logging. BASINMAN is a two-layered (saturated and unsaturated) simple tipping-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 evapotranspiration and crop factors (FAO method).

Application of BASINMAN has not been extensive. All data constraints associated with the FAO method to estimate evapotranspiration and most of the constraints in relation to soil properties and hydrology are applicable to BASINMAN as well. BASINMAN also requires information about irrigation infrastructure including the geometry of drains, supply channels and wells. BASINMAN has been compared with SWAGMAN Destiny, the results of the simulations from the two models being comparable (Wu et al., 1999).

4.1.10. 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 accounts for the effects of topography by using the TOPMODEL wetness index (after Beven and Kirkby, 1979). All physical parameters including salt concentration are averaged over wetness index categories. CATSALT can be used to model land use changes on water quantity and quality. Outputs from CATSALT can be input to flow system models e.g. IQQM.

Spatial climate data required by CATSALT are available from the BoM as well as SILO PPD. Some soil and hydrological characteristics are available from ASRIS. Stream flow data required for CATSALT are generally available from state and territory agencies and spatial coverage of land use is available from a range of sources. CATSALT has only been applied to several catchments in Eastern Australia (Table 13) as it requires some spatial datasets that are not available as Australia-wide coverages, including depth to groundwater and salinity.

4.1.11. IQQM

The IQQM model 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 soil water model component of IQQM is the Sacramento Soil Moisture Accounting (SAC-SMA) model, a conceptually based rainfall-runoff model with spatially lumped parameters (Burnash et al., 1973; Burnash, 1985). The Antecedent Precipitation Index (API) within SAC-SMA is one of the most common methods for simulating rainfall-runoff processes. SAC-SMA can explicitly account for soil moisture changes, while the API methods use indices to simulate the soil moisture conditions. The model attempts to maintain percolation characteristics to simulate streamflow contributions from a basin.

IQQM easily allows other modules to be incorporated and has been used to measure effects of climate change on land use. The IQQM soil water module, SAC-SMA, requires daily evapotranspiration, in addition to rainfall. BoM has spatial estimates of long-term mean monthly and annual evapotranspiration whereas SILO PPD produces daily and monthly spatial estimates of pan evaporation across the continent, which can be used to calculate daily evapotranspiration. SAC-SMA 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. IQQM has already been implemented in major river systems in New South Wales and Queensland (Table 13). It has also been applied in Indonesia, South-east Asia (Mekong River) and Zambia.

4.1.12. REALM

The REALM model is a generalised simulation package for analysing the yield and security of water supplies and evaluating changes in operation of stream flows. It is able to simulate complex water management operating rules with a high degree of flexibility. REALM is similar to IQQM in terms of purpose. The REALM model can use simple models, such as PRIDE, to estimate farm water requirements. REALM is in active use in Victoria, South Australia and Western Australia (Table 13). It can 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. In terms of data constraints, REALM has concerns similar to IQQM.

4.1.13. MSM-BIGMOD

The MSM-BIGMOD model developed by the Murray Darling Basin Commission includes rainfall-runoff relationships, operating rules for storages, irrigation demands, flow and salinity routing, water resource assessment and water accounting (Young et al., 2003). It is a river systems model rather than a whole of catchment model and provides daily flows similar to IQQM's outputs. In terms of data constraints, MSM-BIGMOD has concerns similar to IQQM.

4.2. Limitations of simple models with tipping-bucket approach

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 the early stages of crop growth. WATBAL, GROWEST and PRIDE use evapotranspiration 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 in 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 differences in 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. BiosEquil and BiosEvolve do not take into account the hydrological consequences of aggregating to different boundaries, such as transmission losses, flow routing and base flow.

Simple models with a tipping bucket 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).

4.3. Complex models

Complex models are used for detailed studies of water movement. They simulate runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching within the locations where they are applied. The data requirements of the complex models reflect their original purpose. Water and salt balance models have much greater requirements for soil and solute data. Models designed to study the impacts of crops and other vegetation on water balance require more information about agronomy.

4.3.1. SWIM

Soil Water Infiltration and Movement (SWIM) can be used to simulate runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching. SWIMv1 (Ross, 1990b) uses Richards' equation with an efficient numerical solution. It simulates infiltration, evapotranspiration and redistribution. SWIMv2 (Verburg et al., 1996) combines water movement with transient solute transport and accommodates a variety of soil property descriptions and more flexible boundary conditions. SWIMv2 also includes a numerical solution for the advection-dispersion equation. The model 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 and soil moisture characteristics are also needed.

SWIMv1 uses Richards' equation with an efficient numerical solution. This model is capable of simulating upflow with an acceptable degree of accuracy provided that parameters describing plant leaf area and, particularly, root distribution are adjusted appropriately (White and Walker, 2000). 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).

4.3.2. APSIM SWIM (APSWIM)

SWIMv2 is used as the basis for an alternative water movement model in APSIM (McCown et al., 1995). Thus, APSIM can use SoilWat or SWIMv2 and as a result, APSIM enables these contrasting approaches to be compared readily (McCown et al., 1996). APSWIM calculates all flows of water and nutrients in the soil. APSWIM provides greater scope for evaluating the effects of soil condition, weather and management on infiltration and crop growth (Connolly et al., 2002).

In addition to climate data required in SWIM, APSWIM requires rainfall duration or intensity, which is not readily available for most areas. Most of soil and hydrological information required for APSWIM are site-specific. Sources of spatial information on soil and soil hydrology described in Section 3.2 may not be accurate enough for point-scale models such as APSWIM.

4.3.3. WAVES

WAVES is a biophysical model which predicts dynamic interactions within the soil-vegetation-atmosphere system. Although all of the other models described above are similar in terms of the calculation of actual and/or potential evapotranspiration, WAVES includes physiological control on transpiration as a function of CO_2 assimilation rate, vapour pressure deficit and 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 is generated from the excess of precipitation intensity over soil infiltration rate and the occurrence of precipitation over saturated surfaces. Lateral surface flow that occurs via the saturated water table is described by Darcy's law. WAVES can run either with minimal climate datasets (rainfall and temperature) or additional climate datasets (vapour pressure deficit, solar radiation and rainfall duration).

In addition to standard soil information required by simple multi-layer models, WAVES requires details of soil structure which are not easy to obtain. WAVES also requires management information. WAVES has been 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.

4.3.4. ALSIS

ALSIS, a land surface parameterisation scheme, is developed with an emphasis on soil moisture prediction. ALSIS is essentially a surface hydrologic model for the prediction of evapotranspiration, surface and subsurface runoff and deep drainage by parameterisation and solving the Richards' equation and the temperature diffusion equation for multi-soil layers. The analytical solution to solve Richards equation developed by Broadbridge and White (1988) has been used in ALSIS. The model requires considerable soil and soil water characteristics spatially in its current form, but for initial simulations, it assumes vertically homogeneous soil for the entire continent of Australia.

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 evapotranspiration and decreases runoff and recharge. ALSIS has been applied for soil moisture simulation over the Australian continent (Table 13). 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.

4.3.5. Topog_Yield

The TOPOG framework is composed of a computational and hydrological unit called a "kernel". The kernel consists of a suite of 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 flow strips and is also permitted to reinfiltrate when encountering an unsaturated element.

One of the most sophisticated features of Topog_Yield is the terrain analysis, which is used to create hydrologic units (typically 20×20 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 evapotranspiration processes: canopy interception, plant transpiration and soil evaporation.

Topog_Yield can be used to simulate hydrologic states over long-term sequences, characterised by variable climatic conditions and land use. The model is designed to be used in catchments less than 10 km^2 and ideally for catchments less than 1 km^2. In terms of performance, modelled and observed runoff values compare well (Vertessy et al., 1993). 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. Dividing the landscape into small hydrologic units and catchments based on terrain analysis can be problematic and time-consuming.

4.3.6. CLASS

CLASS was developed to overcome the limitations of CATSALT (Tuteja et al., 2004). It 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 evapotranspiration. 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. It 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 evapotranspiration 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 streams to the catchment outlet using the linear cascade model of Nash (1960) as in Kachroo (1992). Total groundwater discharge from the landscape to streams is routed using a similar approach (Tuteja et al., 2004). 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 has not been applied on the national scale. It is intended for implementation on medium to large catchments to investigate the effects of land use and climate variability on a catchment 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. 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.

4.3.7. 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, 1995, 1996), 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 (1980). SWAGMAN Farm and SWAGMAN Destiny are more widely used. SWAGMAN Farm is a lumped water balance model that 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). Both SWAGSIM and SWAGMAN require all the standard climate data except evaporation. SWAGSIM also requires information about irrigation infrastructure including the geometry of drains, supply channels and wells. SWAGMAN requires more soil hydrological and cropping data, but less hydrogeological data than SWAGSIM.

Calibration and validation of the SWAGSIM and SWAGMAN Destiny models have 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, 1996) have been used for early testing of the model. Simulations of SWAGMAN Destiny showed good agreement 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. 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.

4.4. Limitations of complex models

As stated earlier, complex models in this review are basically defined as models that use Richards' and Darcy's equations. Richards' equation assumes 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 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 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.

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.

5. Concluding remarks and future directions

Soil water models can be categorised in terms of their treatment of the soil profile, evapotranspiration, runoff and drainage. The degree of complexity of a model is based on the level of detail of these treatments. In this review, soil water models have been categorised in terms of their treatment of the soil profile in terms of soil layers. With fixed soil layers, simple soil water models with the tipping bucket approach are divided into single layer or multiple layers. With a continuous soil profile, complex soil water models are divided into one- or two-dimensional flow models.

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 simulations are made. Simple models are useful in large scale modelling where lack of data and limits in understanding of all the factors and processes affecting water dynamics hinders 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.

As more continental scale data become available, moving from simple models to more detailed models may be possible since simple models can improve their simulation of biophysical processes in line with the new data sources to gain more accurate predictions. On the other hand, lack of specific requisite data hampers the use of complex models in wide-range applications and therefore, simplifying model processes should be encouraged to accommodate existing data availability.

Most of the models reviewed here, regardless of the category, have the capacity to be applied anywhere in Australia given that there are 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, in addition to single layer models. Most of the one-dimensional water flow models reviewed are point-based; however, some of two-dimensional water flow models, such as CLASS and Topog_Yield, are spatially distributed.

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 being increasingly used in the process of policy development. Integrative water assessment brings understanding from various water balance and land use components on different scales, in which stakeholders determine their policy making. Catchment-based water models can be integrated into the decision making process involving both scientists and policy makers.

The catchment-based models reviewed in this study (BiosEquil/BiosEvolve, AussieGRASS, AWBM, CATSALT, TOPOG_Yield and CLASS) have been developed relatively recently (since the early 1990s) and continue to be actively researched and improved. They can be useful to gather nationally-consistent information on the water balance, including rainfall, evapotranspiration, runoff and deep drainage. However, at present, there is no comprehensive and consistent source of national information on the water balance across Australia. Therefore, this fundamental knowledge gap needs to be addressed at the national scale.

Improvements need to be done to assess the significance of water intercepting activities based on an understanding of the total water cycle. It is also important to improve modelling approaches 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, land use change, social change and the implementation of new policies and practices.

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