Regional Water Balance: Initial Methods Review 2009

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Regional Water Balance: Initial Methods Review 2009

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Summary

The Bureau of Meteorology has been given the tasks of producing annual National Water Resource Assessments and an annual National Water Account. These investigations require evaluation of annual water flows and storage in regional catchment water balances. This document reviews methods for estimating the water flux and storage terms in a water balance framework that facilitates the evaluation of catchment water balance in a series of pilot study areas. The pilot studies are being undertaken in a range of selected regions (i.e. Murrumbidgee, Melbourne, South East Queensland, Gnangara Mound, Murray Darling Basin, Namoi, Onkaparinga) and are aimed towards building the Bureau's capacity for production of a national water balance and subsequently the National Water Account.

The review proceeds by outlining the water balance framework to be applied and the methods used to populate the framework, given the data that are to be supplied according to the Water Regulations 2008 (Australian Government, 2008b; Australian Government, 2008c). A recommendation is made regarding population of each term of the water balance framework for use in the pilot studies, to be completed in early 2010.

NOTE: It is intended that this review document will be updated annually (after application in the 2009 pilot study, after the first National Water Account due in late 2010, and so on), with details of application of the method. Furthermore, recommendations on methods to be used in subsequent years will be updated annually to reflect the methods available at the time.

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1 Introduction

The Bureau of Meteorology is charged with providing public dissemination of products related to a national water balance for the purpose of periodic water resource assessments and the annual National Water Account, as specified within the *Water Act 2007* (Australian Government, 2007, 2008a). For this purpose, the water balance framework has been defined within *A Proposed National Water Balance Framework* (Barratt, 2008) as:

Definition: *Comprehensive evaluation of the inputs to, outputs from and movements of water within a hydrological entity. It includes precipitation and evapotranspiration, as well as other fluxes of water though the terrestrial environment.*

This resulting proposed framework (or series of water balance structures) was based largely on the lessons learned and recommendations arising from the Baseline Water Resources Assessment conducted as part of the Australian Water Resources 2005 Project (AWR2005 – see http://www.water.gov.au/).

The population of the terms within this framework (e.g. rainfall, evapotranspiration, runoff, surface and groundwater storages, groundwater recharge) depends on both data availability and the applicability of using modelled estimates where data are not available/appropriate. *Water balance terms and their population using Water Act Regulations Data* (Barratt et al., 2008) details two analyses regarding the population of the proposed structures:

- a review of results achieved in populating regional water balances under AWR2005
- an analysis of the amenability of the proposed water balance elements to population by data being received by the Bureau under the Water Regulations 2008 (Australian Government, 2008c).

The review of results found that data accuracy tended to be highest (in terms of estimated percentage uncertainty/inaccuracy for any given water balance term) for major storages and outflow from these storages, and least for groundwater storage volumes. It was also found that many of the terms within the water balance contained no data. That is, as there are no data to be supplied as part of the Water Regulations the component must be fully estimated using a model of some sort. These results suggest that differing levels of effort should be put into estimating the different terms of the water balance so as to reduce the uncertainty of the overall results.

The analysis of the amenability of the proposed framework to population by the data anticipated to be received by the Bureau under the Water Regulations 2008 showed that some measured data can be used directly to populate the water balance, e.g. water storage volume and diversions (distributed and self-extracted). However, most Water Regulations data will require some form of analysis before being input into the framework.

Furthermore, the methods used to estimate each term of the water balance must be able to be applied nationally and should also be self-consistent (i.e. terms within the water balance should be consistent with one another and the observed data). Given the methods identified for populating the water balance terms (and their relative inaccuracies), a detailed review of possible methods for populating the individual terms was undertaken.

1.1 Objective and scope

The purpose of this review document is to recommend options for representation of water fluxes to and from stores and for estimation of the stored water volume in each store, with a particular focus on those water fluxes that are not directly estimated from data gathered as part of the Water Regulations.

The water balance framework used here is based on the detailed water balance framework proposed by Barratt (2008) and subsequently modified by Daamen et al. (A Framework for Estimating Rural and Urban Catchment Water Balance, in prep.). The *detailed* water balance structure was chosen for discussion here (as opposed to the *intermediate* and *simple* frameworks presented by Barratt (2008), as those simpler frameworks can be populated using the detailed framework. Methods for populating all elements of this water balance structure will be surveyed given the data available through the Water Regulations 2008 (Australian Government, 2008c) and subsequent Water Amendment Regulations 2008 (Australian Government, 2008b) (herein collectively called the 'Water Regulations').

Population of the water balance framework is required by September 2009 for a series of selected regions (i.e. Murrumbidgee, Melbourne, South East Queensland, Gnangara Mound, Murray Darling Basin, Namoi, Onkaparinga for the 2006–07, 2007–08 water years) for the purposes of creating a pilot water account. A subset of these regions will subsequently be used to test water balance methods thoroughly as part of the pilot regional water balance 2009 (finalised early in 2010). Recommendations for methods of populating the water balance framework will be made for the purposes of these studies (herein collectively called the 'pilot studies').

1.2 Review outline

The review proceeds by detailing the water balance framework, the Water Regulations data, and the criteria for selecting methods of populating the framework in section 2. Details of the proposed methods for populating the water balance are presented in section 3, followed by the conclusions in section 4.

2 Water balance framework and the Water Regulations data

This section is formulated according to:

- description of the purpose of the water balance framework
- description of the key features of the proposed water balance framework
- detailed description of the components of the water balance framework to be populated
- description of the available data - in particular those to be provided as part of the Water Regulations
- description of the criteria by which methods will be selected for the initial pilot water balance studies to be undertaken late in 2009 and early 2010.

2.1 Purpose of the water balance framework

The water balance framework aims to provide a conceptual basis over which fluxes/storages can be estimated for the purpose of water resource assessments and the National Water Account. Water resource assessments require estimation of the water availability over a given time period, whereas the National Water Account has the additional requirement of estimation of water use over a given time period. The conceptual water balance framework must therefore allow distinction between stores (e.g. groundwater versus surface water), determination of the amount of available water in each store, and finally determination of fluxes to/from each store. Furthermore, the conceptual framework must allow the estimation of water use, which is limited by water availability.

For illustrative purposes, examples of fluxes from surface-based stores (e.g. rivers, dams, soil moisture) and groundwater stores (e.g. aquifers) are shown in Figure 1 and Figure 2, respectively. Fluxes associated with the surface water and groundwater stores include:

- precipitation – snow and rain on the land and on storages
- evapotranspiration – from the land and from storages (dams, lakes)
- runoff/discharge – typically as a result of precipitation
- stream/river flow
- seepage/recharge – from the land and surface storages
- surface water – groundwater interactions
- regional groundwater flow
- human-related transfers from each store (e.g. managed aquifer recharge).

Examples of fluxes related to rural and urban water use are shown in Figure 3 and Figure 4, respectively. Examples of uses include:

- irrigation water use and returns
- private stock and domestic water use
- bulk urban water use
- interbasin transfers.

The conceptual water balance must be able to describe this wide range of natural fluxes and those influenced by humans (including water use). A water balance framework based on four conceptual stores (rather than simply surface water and groundwater stores) is required to elucidate water availability and water use adequately.

The proposed conceptual framework is described below.

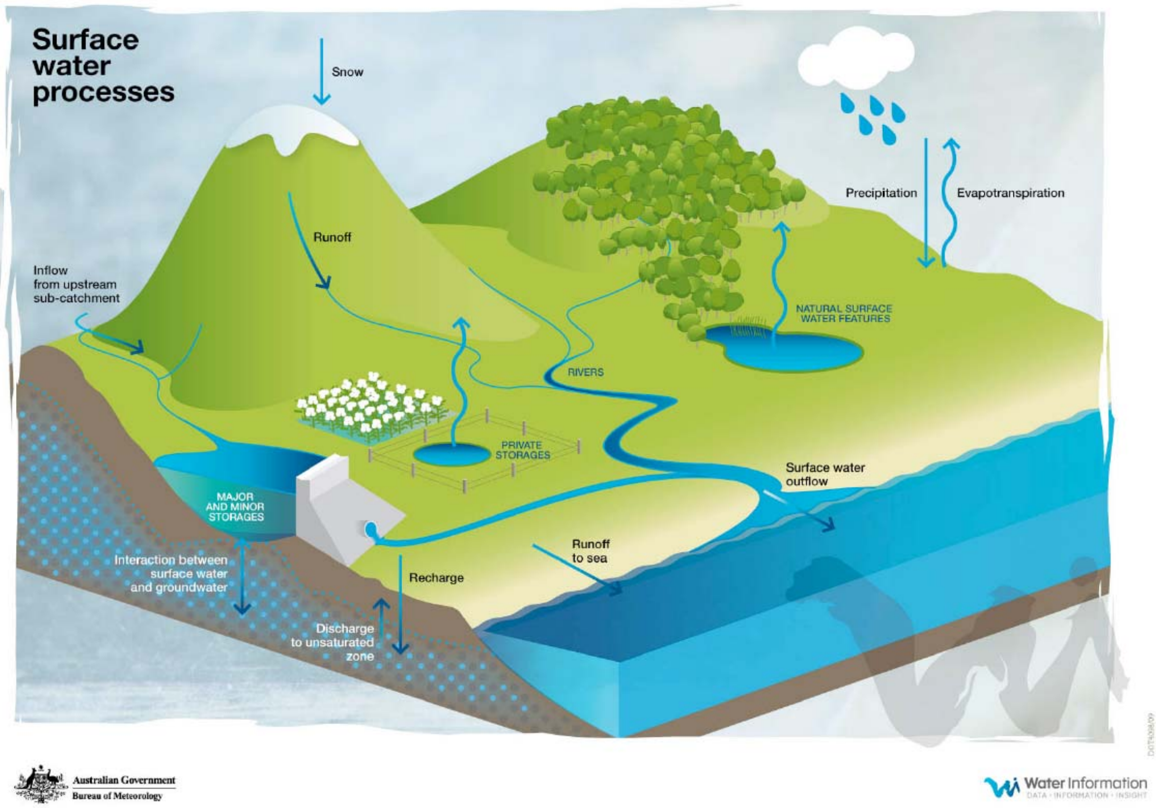

Figure 1. Examples of fluxes associated with surface water processes

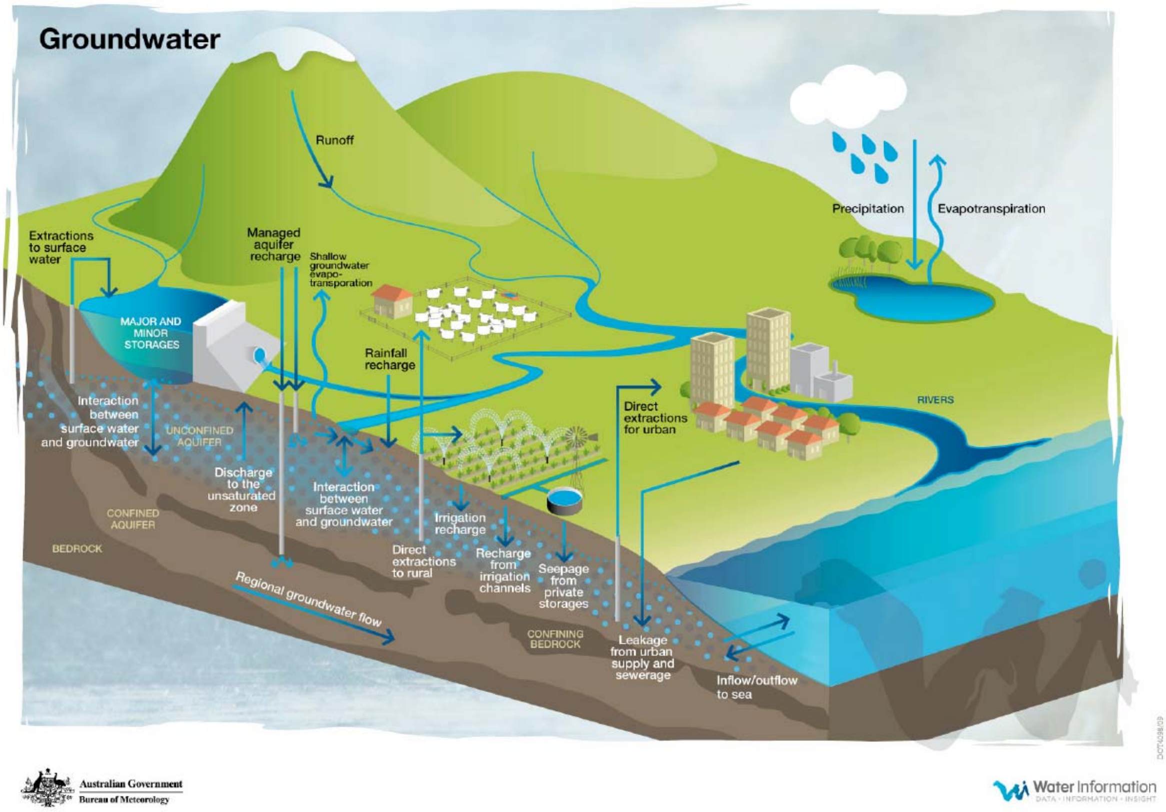

Figure 2. Examples of fluxes associated with the groundwater store

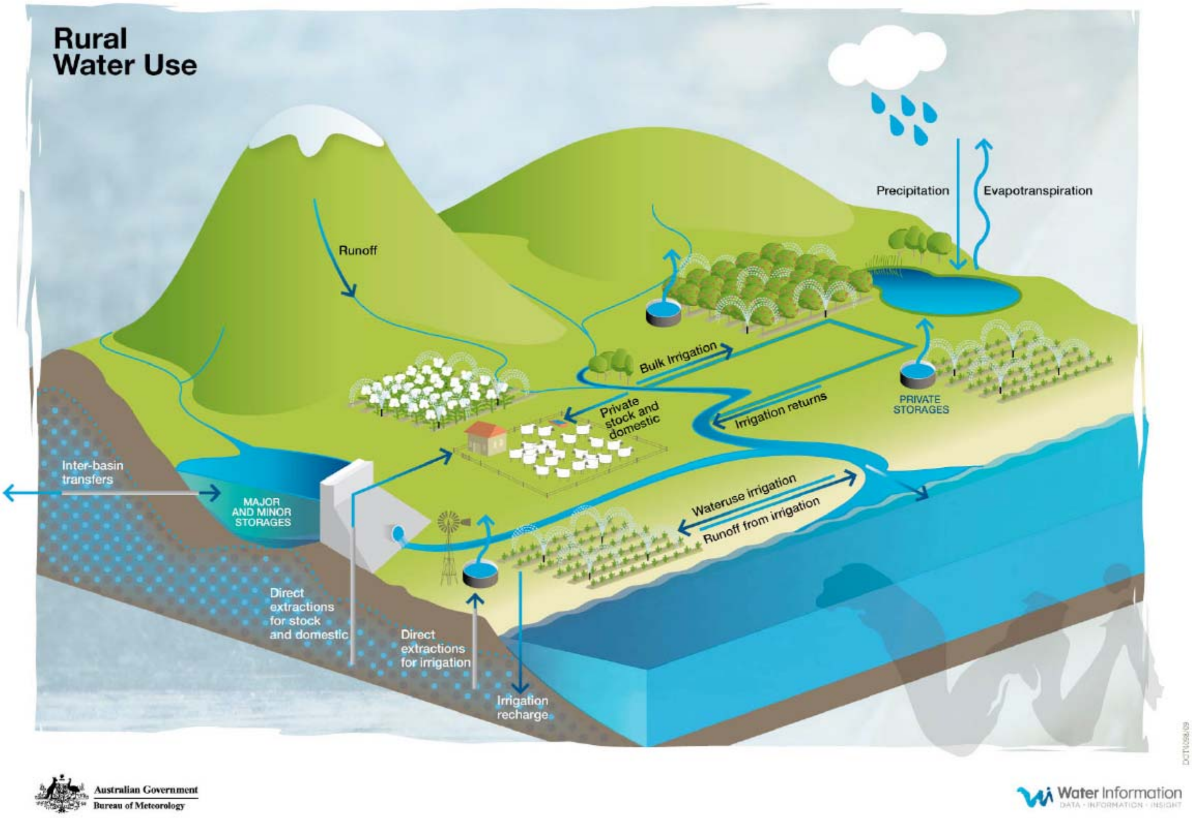

Figure 3. Examples of rural water use fluxes

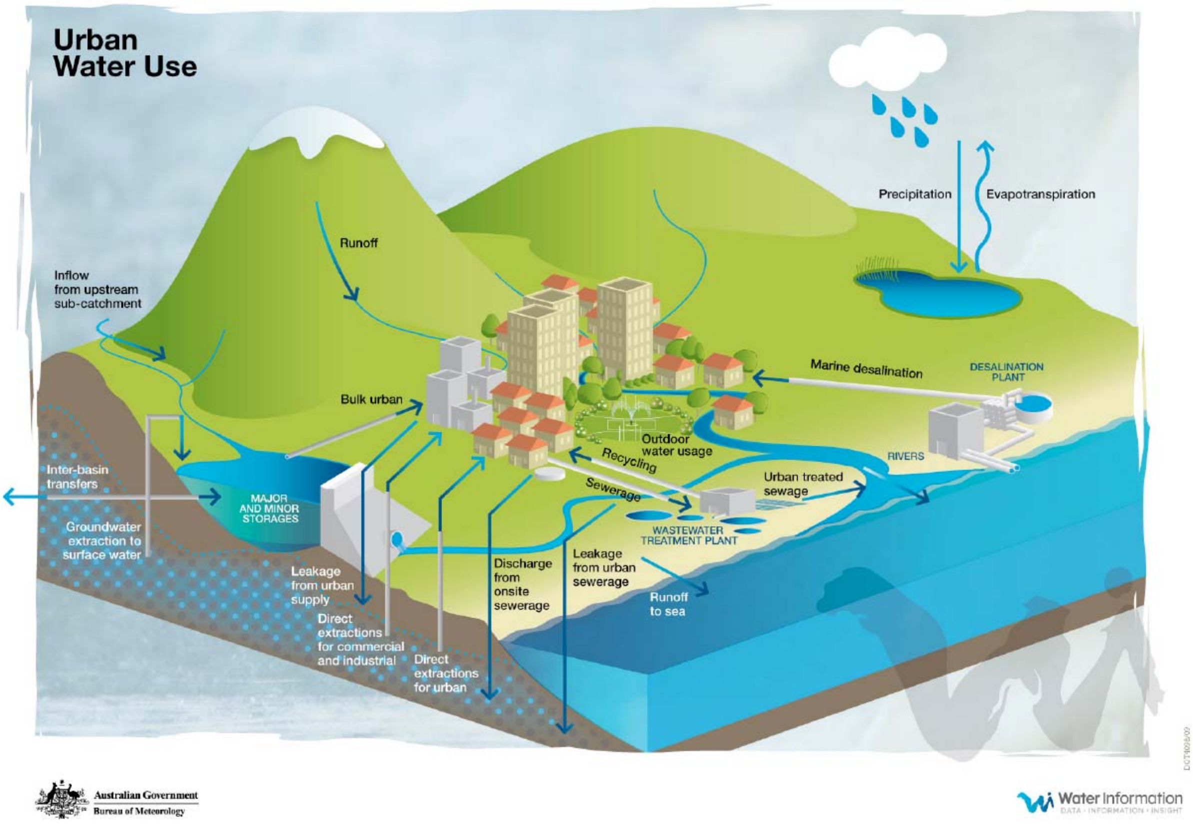

Figure 4. Examples of urban water use fluxes

2.2 The water balance framework key features

The water balance framework used here is based on that proposed by Barratt (2008). The key features of the water balance structures defined by Barratt are that it:

- focuses on the fluxes of water through the physical landscape (hydrosphere), encompassing both natural and anthropogenic processes
- strictly adheres to the concept of a mass balance (i.e. Inputs = Outputs + ΔStorage) applied to a fixed volume, that is, a three-dimensional box, for a fixed period of time. A water balance may contain multiple input, output and storage terms, depending on the level of detail required.
- is applied to a physically defined entity, such as a (surface) hydrological catchment or basin, which has clearly defined boundaries. The lower boundary is set below a depth where the groundwater level fluctuates.
- is consistent with the way in which the concept of water balance is used in hydrological modelling and the conceptualisation of the hydrological cycle, and is bounded by the energy balance via evapotranspiration.

A series of water balance structures based largely on the lessons learned and recommendations arising from the Baseline Water Resources Assessment conducted as part of the Australian Water Resources 2005 (AWR 2005) project were proposed by Barratt (2008). The three possible frameworks presented for the water balance were:

1. use the existing AWR 2005 framework
2. develop a framework of three nested water balances ranging from simple (12 terms) to detailed (100 terms)
3. classify regions into broad land use classes (urban, bulk irrigation or rural/natural), with a different water balance for each class.

Choice of a particular framework depends on the data availability and the end use for which the results are to be presented. Therefore, a definitive statement on which framework to use was not suggested by Barratt (2008). It was identified that use of the existing AWR 2005 framework, while providing direct comparability to a past water resource assessment, had the drawback that the methods applied were often inconsistent among and across regions. Use of this framework is therefore not considered further as a candidate. However, AWR 2005 does provide the basic structure upon which options 2 and 3 were produced. As the detailed water balance suggested in option 2 can be aggregated to the simple water balance, and can also be used in a scheme that classifies regions into broad land use classes (option 3), the detailed water balance framework is used here as the generic water balance structure to be populated. It is noted that the detailed water balance framework (and component stores and fluxes) are defined by Barratt (2008) and shall be used here for the definition of a detailed water balance structure.

As defined by Barratt (2008) it is intended that a subcatchment water balance (be it in an urban, bulk irrigation or rural/natural context) will be estimated every year using the concept of three water stores within a subcatchment and a water transport system, as shown in the conceptual form. That is, the following conceptual stores are defined as:

1. the Landscape (land surface and soil) water store
2. the Surface water store
3. the Groundwater store
4. the Water transport system.

A conceptual diagram of the subcatchment water balance framework is shown in Figure 5.

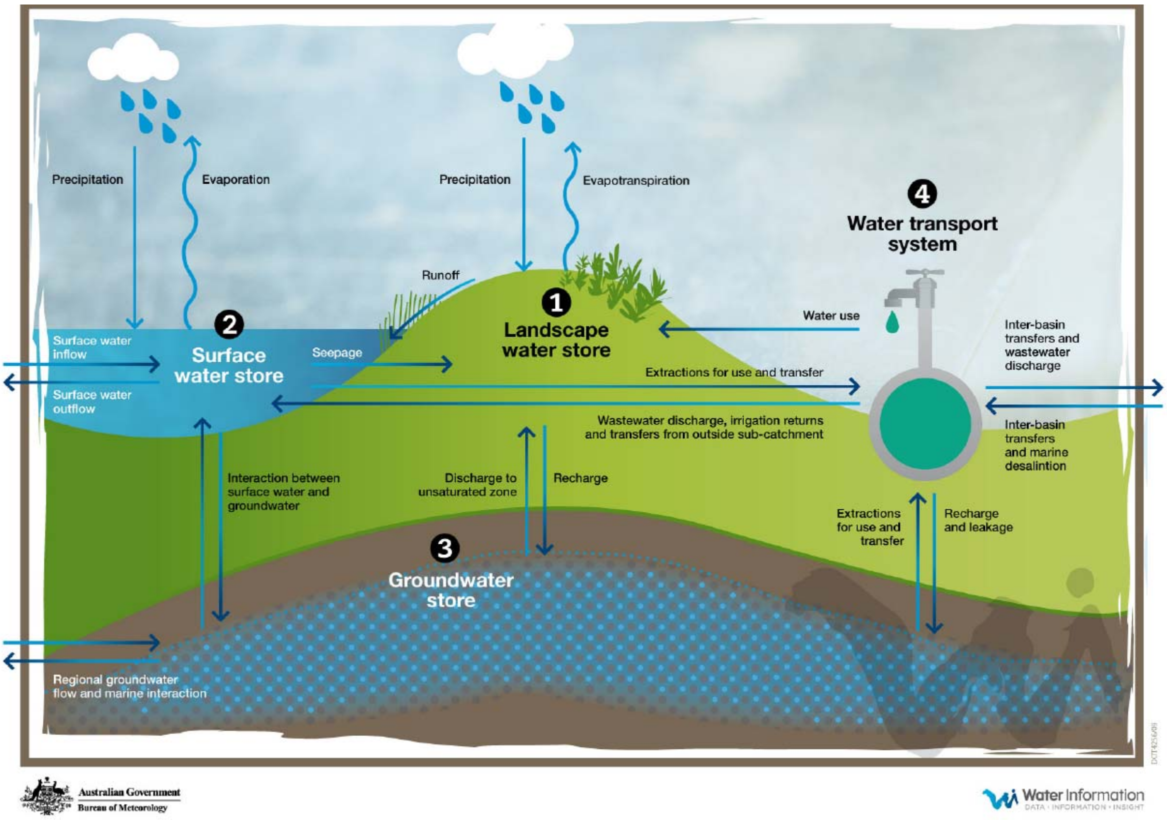

Figure 5. Conceptual diagram of subcatchment water balance framework

The stores are further described below. Briefly, the Surface water store is water in the primary river beds and water storages, and the Water transport system is water that has been diverted for human use in irrigation channels and urban water transport systems (closely associated with the Surface water store). The Groundwater store and the Landscape water store (surface and soil water store) are largely as their names suggest.

As previously stated, the water balance must strictly adhere to the concept of a mass balance over the component stores for a given time period. Therefore, for a given time period, the calculation of the water balance for each store proceeds by:

- estimating the volume of water held in the stores at time t_0
- estimating the flux to and from each store over time t_0 to t_1
- estimating the volume of water held in the stores at time t_0 to t_1

Therefore, the stores and fluxes to/from each store are further defined here and related to the terms within the detailed water balance framework of Barratt (2008), so that methods of estimation can be discussed given the available data.

2.3 Components of the detailed water balance framework

The storage terms to be estimated as part of the detailed water balance framework are presented in the first column of Table 1. The flux terms are also presented for the Landscape water store (Table 2), the Surface water store (Table 3), the Groundwater store (Table 4), and the Water transport system store (Table 5).

Note that flow components between these four stores occur twice in the tables: once as an outflow from one store and a second time as an inflow to another store.

Table 1. Storage terms to be estimated and possible means of estimation using Water Regulations data

Term	Section
1 Landscape Water Storage	**3.3**
Snow	3.3.1
Interception – vegetation canopies, surface roughness, rock surfaces, urban impervious	3.3.2
Water in uplands storage (swamps/depressions)	3.3.3
Soil – unsaturated zone	3.3.4
2 Surface Water Store	**3.4**
Natural surface water features	3.4.1
River channels – rivers/streams (defined) and urban drain	3.4.2
Major storages (maximum volume > 1GL)	3.4.3
Minor storages (100ML > maximum volume > 1 GL)	3.4.4
Private storages – Farm dams, Rainwater tanks, greywater, off-stream storages	3.4.5
3 Groundwater Store	**3.5**
Renewable non-saline groundwater (confined and unconfined aquifers)	3.5.1
Renewable saline groundwater	
Non-renewable groundwater	
4 Water Transport System	**3.6**
Water Tranposrt System store	3.6.1

Table 2. Landscape water flux terms to be estimated and flow component labels

	Category of Inflow/Ouflow	Flow component	Section
Inflow to ① Landscape water store	From outside subcatchment	Precipitation (other than snow)	3.2.1
		Snow	3.2.1
	From ③ Groundwater store	Capillary rise	3.5.5
	From ④ Water transport system	Water use – rural irrigation	3.6.10
		Water use – urban irrigation/outdoor	3.6.11
		Wastewater/recycled water for irrigation (urban/rural)	3.6.12
		Seepage from septic tanks	3.6.13
		Water transport system leakage (rural/urban)	3.6.14
		Seepage from irrigation channels	3.6.15
Outflow from ① Landscape water store	Exiting subcatchment	Evapotranspiration	3.3.6 (3.2.2)
	To ② Surface water store	Runoff	3.3.7
		Interflow	3.3.8
	To ③ Groundwater store	Recharge	3.5.3

Table 3. Surface water flux terms to be estimated and flow component labels

	Category of Inflow/Ouflow	Flow component	Section
Inflow to ② Surface water store	From outside subcatchment	Precipitation on to water surfaces (storages, natural water features, river channels)	3.2.1 (3.4.6)
		Inflow from upstream subcatchment	3.4.8
	From ❶ Landscape water store	Runoff to rivers	3.3.7 (3.4.6)
		Runoff into natural surface water features	3.3.7 (3.4.6)
		Runoff to major and minor storages	3.3.7 (3.4.6)
		Runoff to private storages (farm dams and rain tanks etc) (account for farm dam overflow)	3.3.7 (3.4.6)
		Interflow	3.3.8 (3.4.6)
		Runoff from irrigation (irrigation drainage)	3.3.7 (3.4.6)
	From ❸ Groundwater store	Discharge from groundwater to minor/major storages	3.5.4
		Discharge from groundwater to private storages	3.5.4
		Discharge from groundwater to natural surface water features	3.5.4
		Discharge from groundwater to rivers	3.5.4
		Extraction from groundwater to surface water	3.5.7
	From ❹ Water transport system	Urban wastewater/effluent	3.6.16
		from Marine Desalination	3.6.17
		Inter-Basin transfers in	3.6.18
		Rural Irrigation returns	3.6.19
Outflow from ② Surface water store	Exiting sub-catchment	Evaporation from major and minor storages	3.4.7 (3.2.2)
		Evaporation from private storages	3.4.7 (3.2.2)
		Evaporation from natural surface water features	3.4.7 (3.2.2)
		Evaporation from rivers	3.4.7 (3.2.2)
		Evaporation from irrigation channels	3.4.7 (3.2.2)
		Surface water outflow (flow in rivers, drains, swamps, stormwater) inc. Surface water outflow from coastal catchments to the sea	3.4.8
	To ❸ Groundwater store	Leakage/seepage from private storages (e.g. farm dams)	3.4.9
		Seepage from major and minor storages	3.4.9
		Seepage from rivers (including floods)	3.4.9
		Seepage from natural surface water features	3.4.9
		Managed Aquifer Recharge	3.4.10
	To ❹ Water transport system	Bulk urban	3.4.11
		Bulk rural irrigation	3.4.12
		Private irrigation	3.4.13
		Private stock and domestic	3.4.14
		Private commercial/industrial diversions	3.4.15
		Usage from private storages (farm dams and rainwater tanks etc)	3.4.16
		For Inter-basin transfers out	3.4.17

Table 4. Groundwater flux terms to be estimated and flow component labels

	Category of Inflow/Ouflow	Flow component	Section
Inflow to ③ Groundwater store	From outside subcatchment	Regional groundwater flow (shallow and deep)	3.5.2
		Marine Inflow	3.5.6
	From ① Landscape water store	Groundwater recharge from rainfed areas	3.5.3
		Groundwater recharge from irrigation areas	3.5.3
	From ② Surface water store	Seepage/recharge from natural surface water features	3.5.4 (3.4.9)
		Seepage/recharge from rivers including floods	3.5.4 (3.4.9)
		Seepage from major and minor storages	3.5.4 (3.4.9)
		Leakage/seepage from private storages (e.g. farm dams)	3.5.4 (3.4.9)
		Managed Aquifer Recharge	3.4.10
	From ④ Water transport system	Leakage/seepage from irrigation channels/urban supply	3.6.20
Outflow from ③ Groundwater store	Exiting subcatchment	Regional Groundwater flow out of entity (shallow and deep)	3.5.2
		Marine outflow	3.5.6
		Shallow groundwater ET	3.5.5
	To ① Landscape water store	Capillary rise	3.5.5
	To ② Surface water store	Extraction from groundwater to surface water	3.5.7
		Discharge to major and minor storages	3.5.4
		Discharge to private stores (farm dams)	3.5.4
		Discharge to natural surface features	3.5.4
		Discharge to rivers	3.5.4
	From ④ Water transport system	Direct extractions from groundwater	3.6.5
		For Inter-basin transfers – out	3.4.17

Table 5. Water transport system flux terms to be estimated and flow component labels

	Category of Inflow/Ouflow	Flow component	Section
Inflow to (4) Water transport system	From outside subcatchment	Inter-basin transfer	3.6.2
		Marine desalination	3.6.3
	From (2) Surface water store	Bulk urban water	3.4.11
		Bulk rural irrigation	3.4.12
		Private irrigation	3.4.13
		Private stock and domestic	3.4.14
		For Inter-basin transfers – out	3.4.17
		Private commercial/industrial diversions	3.4.15
		Usage from private storages (farm dams and rainwater tanks etc)	3.4.16
	From (3) Groundwater store	Direct extractions from groundwater	3.6.5
		Inter-basin transfers – out	3.6.6
Outflow from (4) Water transport system	Exiting subcatchment	Marine outflow of wastewater/effluent	3.6.7
		Evaporation from irrigation channels	3.6.8
		Inter-basin transfer	3.6.6
	To (1) Landscape water store	Water use – rural irrigation	3.6.10
		Water use – urban irrigation/outdoor	3.6.11
		Wastewater/recycling for irrigation/outdoor	3.6.12
		Seepage from septic tanks	3.6.13
		Water transport system leakage (rural/urban)	3.6.14
		Seepage from irrigation channels	3.6.15
	To (2) Surface water store	Urban wastewater/effluent	3.6.16
		From Marine Desalination	3.6.17
		Inter-basin transfers in	3.6.18
		Rural Irrigation returns	3.6.19
	To (3) Groundwater store	Leakage/seepage from irrigation channels and urban supply	3.6.20

2.4 Data, Water Regulations and estimation methods

The fundamental data with which the water balance framework will be populated is based on the data required to be given under the Water Regulations. These Water Regulations require various organisations to give electronic water information that is in their possession, custody or control to the Bureau of Meteorology (the Bureau) for the purposes of water accounting and assessment. A range of data types is to be supplied to the Bureau, stratified according to a set of categories listed in Appendix A.

2.5 Criteria for selection of methods for population of the water balance framework

2.5.1 Criteria applied for 2009 pilot study purposes

The publication of periodic water resource assessments, as required within the Bureau's new role defined by the *Water Act 2007* (Australian Government, 2007; see www.environment.gov.au/water/action/water-act0708.html), requires calculation of the storage and flux terms of the water balance. Section 2.3 details the proposed water balance framework within which these Water Resource Assessments and Accounts (WRAAs) are to be undertaken. Population of the terms of this framework are the focus of this section, with recommendations provided for each term.

The methods for population of the water balance framework are assessed according to the following essential criteria:

- Methods must be applicable nationally, given the Water Regulations data within the 2009 pilot water balance studies, and can be used subsequently within the pilot water accounts scheduled to be published December 2009.
- Methods must be able to be produced/updated nationally on a monthly basis, and this information is then aggregated to the annual scale for the purposes of an annual water resource assessment and accounts.
- The minimum spatial scale used for assessment must facilitate water resource assessment and accounting by local and regional jurisdictional bodies and must thus be at the catchment (or subcatchment) scale.

Other factors contributing to selection:

- magnitude: more effort should be expended on quantifying those terms that will be widely used and are of a large magnitude than on those terms that are of little interest and are of small magnitude. In some cases this results in certain fluxes or storages being neglected for the purposes of the 2009 pilot studies.
- transparency and uncertainty: the water balance should be transparent with regards to the accuracy of the information it presents. To be defensible, the efficacy of approaches available to parameterise the selected methods/model(s) in areas where little or no observed data are available needs to be demonstrated. Whereas a strict definition of adequacy is not possible (as that will differ with the term, location, use and time), ensuring that an estimate of the uncertainty/reliability of given terms is possible would provide a means for judging and improving on estimation of water balance terms.
- consistency versus local applicability: the criteria above do not necessarily preclude using differing methods for population of individual terms in differing regions, depending on the data availability and applicability to the particular hydrologic regime. However, allowing differing methods for every region removes region-to-region consistency. This issue will be approached in future by using differing types of estimation, depending on the particular level of water balance framework that is being populated (e.g. simple, intermediate, detailed), with the level chosen depending on data availability. However, for the initial pilot methods a single method of estimation is recommended for each individual term so as to provide a baseline detailed water balance methodology. This issue will be revisited following the 2009 pilot studies.

WRAA studies undertaken previously provide some guidance as to the plausibility of using certain methods for populating the terms of the water balance. WRAA studies have been undertaken nationally over Australia five times in the last 50 years (McDonald et al., 1999), with the *Australian Water Resources 2005* (AWR 2005, National Water

Commission, 2007; see www.water.gov.au), the *National Land and Water Resources Audit* (National Heritage Trust, 2001; see www.nlwra.gov.au) and the *1985 Review of Australia's Water Resources* (Department of Primary Industries and Energy, 1987) being the most recent. Notably, CSIRO has also produced a detailed assessment of current and future water availability for the Murray-Darling Basin Sustainable Yield (MDBSY) project (CSIRO, 2007), and other subsequent studies are being undertaken for other areas within Australia (see http://www.csiro.au/partnerships/SYP.html).

The most recent studies (AWR 2005 and MDBSY) are considered here to be the baseline methodologies for water resource assessment. Population of terms for each assessment study involved:

- AWR 2005: Incorporation of continent-wide modelling using a physical water balance model (with rainfall, evapotranspiration, soil moisture, runoff and recharge modelled in a steady-state model) coupled with jurisdictional data to ensure consistency of jurisdictional reporting.
- MDBSY: Modelling of individual components of the water balance separately.

In addition to the aforementioned studies, currently available methodologies based on those being developed within the WIRADA (the Water Information Research and Development Alliance between the Bureau and CSIRO's Water for a Healthy Country Flagship - see www.bom.gov.au/water/wirada) will also be considered. It is noted that the research for servicing WRAA needs is in the early stages of a multi-year plan. It is expected that although such tools are not currently available, many such tools developed as part of WIRADA will replace the methods being used in the 2009 pilot accounts over subsequent years.

2.5.2 Internal consistency, closing the water balance, reconciliation and estimation of uncertainty

It is noted that internal consistency, reconciliation and estimation of uncertainty are important considerations in the selection of methods for populating the water balance. Internal consistency is used here to describe estimation techniques that are consistent with one another within the context of estimation of terms within the water balance framework. For example, the estimation of recharge from surface water modelling may be consistent/inconsistent with the method of estimating recharge from groundwater modelling. Reconciliation of these inconsistent components of a water balance is therefore required in such a case if a single figure is to be entered for a given component. This reconciliation is undertaken by a process called closing the water balance (sometimes coupled with uncertainty estimation), as described below.

Internal consistency of methods used to estimate the water balance components is considered to be important. Some examples are:

- The method used to estimate one component of inflow (e.g. diffuse recharge to 'groundwater') should use the same assumptions about the nature and state of the store as another method used to estimate another component of inflow or outflow (localised recharge to 'groundwater', or regional groundwater flow out of the 'groundwater store').
- It would be inappropriate, for example, to use the WaterDyn model estimate of evapotranspiration (ET) together with a runoff estimate from another model, because the ET estimate is made in conjunction with the WaterDyn runoff estimate. Briefly, WaterDyn is a one-dimensional dynamic model for soil water and green-leaf carbon that uses a rainfall grid as an input and estimates soil moisture, actual evapotranspiration, drainage and runoff – see Section 3.3.7.

At this early stage of development of populating the water balance framework, full internal modelling consistency is not possible. This is because single models (or a series of

dependent models) are currently not available to produce the range of water balance fields required. There are models that can provide many components of the water balance (e.g. the soil water accounting models used within the Australian Water Availability Project (AWAP; Raupach et al., 2008) and the water balance modelling of Zhang et al. (2008). However, these methods do not incorporate all terms required (e.g. irrigation, water use, routing of streamflow). As a consequence of this, a method for reconciling estimates of the terms produced from differing methodologies is required for use within the pilot water balance studies.

Even in cases of inconsistency, methods of reconciling inconsistencies should be applied as far as possible, so that a single value can be entered for a given component of the water balance framework or account. This process is termed reconciliation. In the simplest case of reconciliation a water balance is 'closed' by the inclusion of an error term for a given store. That is, if all components of the water balance are calculated according to mass balance, where all components (inputs, outputs and change in storage) are estimated, the water balance can be closed by the following equation:

Inputs - Outputs – Change in storage = error term

where the error term (when compared with the magnitude of the component terms) gives an indication of the reliability of the given water balance calculation. This error term may be calculated for the entire water balance, or over any component of the water balance over which mass balance holds.

Ideally, the uncertainty associated with estimates of water fluxes and of water storage volumes would be produced in the population of the water balance framework. Apart from allowing transparent estimation of the component accuracy, such an approach would allow uncertainty reconciliation techniques to be applied, such as those used by Lowe et al. (2009b). Such techniques essentially rely on reconciling estimates of uncertainty identified for two opposing methods, with the overlapping range for the two estimates providing the final reconciled uncertainty range.

Ideally the water balance should close for each store within the uncertainty of estimation. However, estimation of uncertainty of individual terms is considered outside the scope of the pilot studies, with estimation of individual terms being the focus initially. Given this, simple reconciliation using closing of the entire water balance with an error term is recommended. The intention is to highlight any inconsistencies in methods and develop an approach to reconciliation between estimates. A water balance will be undertaken for the three conceptual stores (Landscape Water Store, Surface Water Store, and Groundwater Store) to allow the magnitude of the error term for each conceptual store to be compared. In addition, the water balance for the pilot catchments should, at the very least, provide a qualitative discussion about the relative confidence that can be placed in the values reported for each term.

General approaches to uncertainty of estimation are being developed within other parts of the Bureau's program. A framework for uncertainty and reconciliation of a water account is being investigated as part of the WIRADA WRAA project (CSIRO, 2009; van Dijk, 2009). Furthermore, the Extended Hydrological Prediction section (within the Bureau) is trialling Bayesian inference-based predictive uncertainty estimation methods for its operational seasonal forecasting products (Tuteja et al., 2009). Formal uncertainty estimation within hydrological models is being trialled using the Bayesian total error analysis (BATEA) framework (Kavetski et al., 2006; Kuczera et al., 2006) applied to rainfall–runoff models. These methods will be considered for catchment water balance calculations in future given a sufficient state of development.

It is highlighted that a whole-of-system model – the Australian Water Resources Assessment Model (AWRAM: Crosbie et al., 2008; Shao et al., 2008; van Dijk, 2008; Viney, 2008) is being developed over a multi-year period as part of the WIRADA WRAA project to service the Water Resource Assessment and Accounting retrospective water

balance estimation needs. An initial prototype landsurface model has been developed (OCCAM: van Dijk and Renzullo, 2009; van Dijk et al., 2009). This prototype will be compared with other methodologies through benchmarking studies (Viney, 2009), with the initial AWRAM land surface hydrology scheme chosen as a result of that study. The development of the AWRAM will be complemented by development (and use of existing tools where appropriate) of groundwater, water use and river-system modelling. Such a whole-of-system approach is attractive in that it is inherently self-consistent. However, the difficulty with such a model arises with merging the model with the available data. Data fusion techniques (including data assimilation) allow dynamic updating such that the estimates made from the model are consistent with those of the data. This model is in an early development phase, with a focus on the incorporation of remotely sensed (e.g. satellite) estimates of precipitation, soil moisture and other variables into the model. The method is not currently available, but it is anticipated to be available for evaluation purposes in 2010.

Recommendation:

It is recommended that closing of the water balance be used for testing the individual stores and overall water balance reliability. Reconciliation methods (e.g. CSIRO, 2009; Lowe et al., 2009b) should also be trialled on some individual components/stores as a means of developing the method for potentially more widespread application in the following year.

3 Review of methods

3.1 Methods for populating a water balance

Methods for estimating the water balance are evaluated in this section of the report, beginning with the climatological fluxes (section 3.2: precipitation and evapotranspiration). Techniques for estimating each storage and flux term are discussed in turn for each component of the conceptual framework – Landscape water store (section 3.3), Surface water (section 3.4), Groundwater (section 3.5) and Water transport system (section 3.6) – in accordance with the structure presented in Table 1 to Table 5. The data types to be supplied by various agencies under the Water Regulations are presented within Appendix A.

3.2 Climate flux terms

3.2.1 Precipitation (rainfall and snow)

Precipitation (including snow) needs to be added to the water balance as an input flux to the Landscape water (Table 2) and the Surface water (Table 3) stores. Precipitation data are also used as inputs to methods for estimating other components of the water balance, e.g. rainfall is used as an input to rainfall–runoff models for runoff estimation.

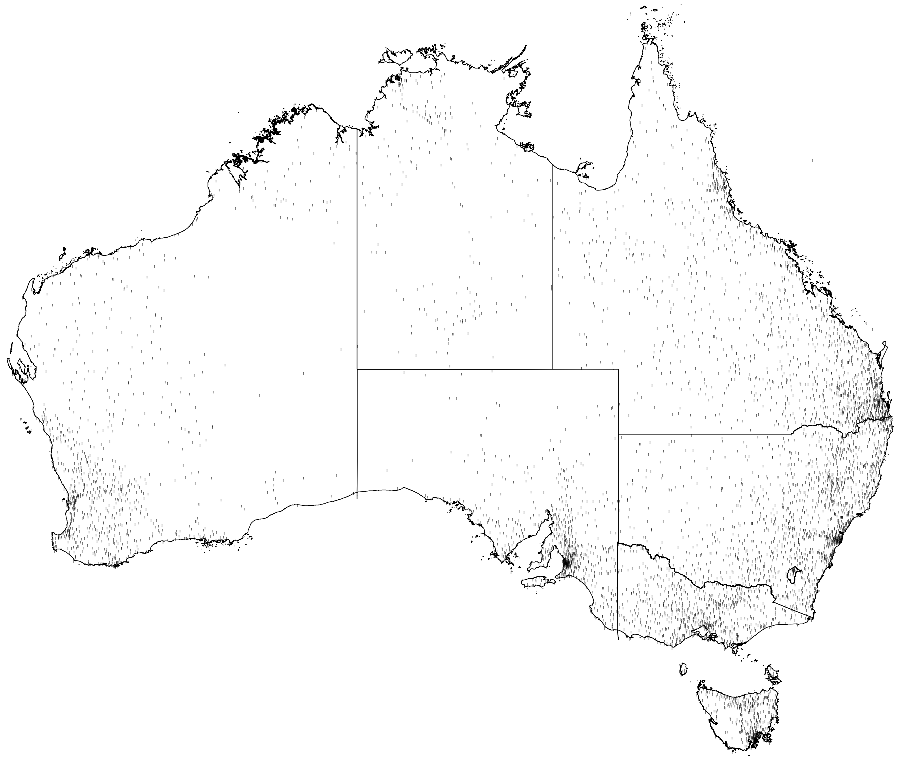

Figure 6 Bureau of Meteorology Daily rainfall station network as at January 2008

Precipitation data are collected within Australia in a range of forms (subdaily/daily gauge recorded and radar/satellite derived estimates) from various agencies (see http://www.bom.gov.au/hydro/wrsc for a station catalogue). These data are usually interpolated/spatially averaged in some form for modelling use; the spatial and temporal resolution of the data depends on the application. Methods used to estimate precipitation spatially differ between agencies, depending on the data used. Within the Bureau, precipitation data are currently collected on a daily basis at 6500 gauge sites spread

throughout Australia (see Figure 6 for locations of sites) and at a subdaily scale at over 2000 sites. Precipitation can also be estimated from the 60 radars Australia-wide (see Figure 7) at 10-minute intervals. However, radar rainfall estimates for only the four high-quality Doppler radar sites are currently bias-corrected using local subdaily rain gauges. Many more daily and subdaily rainfall gauges are operated by other organisations (e.g. municipal water suppliers), with rainfall data measured by these operators scheduled to be supplied as part of the meteorological data supplied in accordance with the Water Regulations (4a). Precipitation estimates are also available from external agencies. These estimates are based on satellite measurements, providing instantaneous estimates at approximately 3-hourly intervals (see Renzullo et al., 2008 for an attempt at using satellite data to estimate 9 am to 9 am rainfall). Note that the type of precipitation (e.g. rainfall or snow) is recorded in the case of daily rainfall data. However, products derived from these data (see below) typically do not differ between the two types.

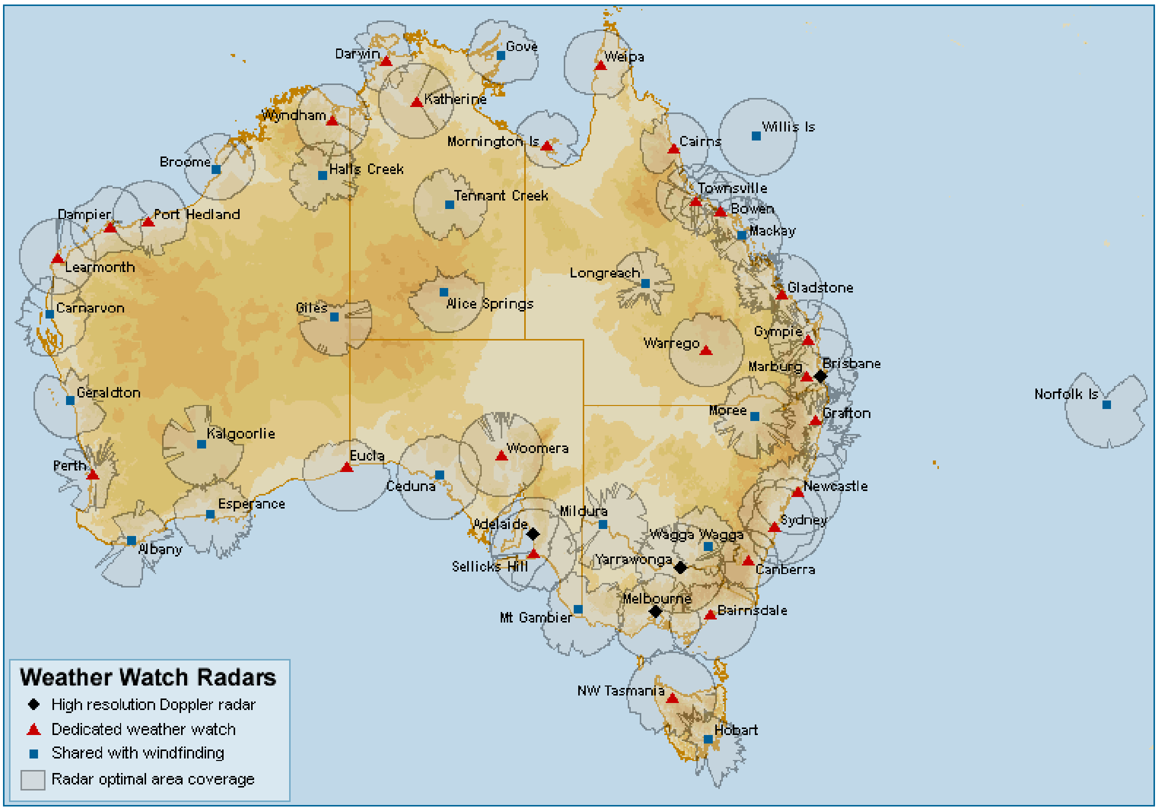

Figure 7 Bureau of Meteorology radar network as at January 2009 (source: http://www.bom.gov.au/weather/radar/about/radar_coverage_national.shtml)

For the purposes here, spatial precipitation (at a subcatchment scale) at a minimum of a daily temporal resolution is required for all modelling purposes. No product currently incorporates the range of observed data available (gauge, radar, satellite) to produce an estimate of daily rainfall nationally, as producing such an estimate given the spatial variability of rainfall is quite complex. However, two products currently exist for interpolation of daily rainfall (and patching of missing records) over the 0.05° (~5-km) grid based on the Bureau's daily network. These are the SILO daily rainfall dataset, based on ordinary kriging (Jeffrey et al., 2001; see www.longpaddock.qld.gov.au/silo) and the dataset supplied by the Bureau as part of the AWAP based on the Barnes analysis method (Jones et al., 2009; denoted BAWAP - see www.bom.gov.au/jsp/awap/rain/index.jsp). Both methods have an operational product based on immediately telemetered daily rainfall data (approximately 1500 sites) and data ingested into the Bureau's database at later dates (approximately 4000 sites). These methods were recently compared in a cross-validation analysis for the period 2001–2007 (Beesley et al., 2009); it was found that the methods performed similarly for the period, with daily RMSEs of 3.35 and 3.06 mm for the BAWAP and SILO methods, respectively. It is noted that the methods used for cross-validation were not identical (SILO used leave-one-out cross-validation, utilising only

those Bureau sites that had no missing/accumulated records in a given month, and the BAWAP method used 5% cross-validation incorporating all sites) and differing sites were used in each analysis. Thus a definitive suggestion as to which method represents the observed rainfall characteristics better was impossible given the supplied data. However, it is clear that both methods perform similarly across Australia, with a tendency to underestimate rainfall for sites/occasions that have relatively high rainfall amounts. Both methods are considered as possible candidates and appropriate for use within the Bureau for WRA assessment purposes. It is noted that the SILO gridded daily rainfall dataset was used within the catchment modelling undertaken within the MDBSY Project (and subsequent Sustainable Yield projects), whereas early versions of the BAWAP gridded rainfall dataset have been used to provide contextual climate information within Water 2010 (Welsh et al., 2007; see www.daff.gov.au/brs/climate-impact/water-2010) and AWR 2005. Both methodologies have been producing daily estimates of gridded rainfall nationwide since 2001 and can therefore be considered to be robust operationally.

Further work is under way as part of the WIRADA Precipitation and Evapotranspiration Project (Renzullo and King, 2008) to incorporate satellite data into the gridded estimation of daily rainfall amounts: see Oke et al. (2009) and Li and Shao (2009) for initial attempts at using TRMM Multi-satellite Precipitation Analysis system products coupled with the Bureau's daily gauge data. Although there are many Water Regulations rainfall data to be supplied to the Bureau (e.g. From tipping bucket gauges not operated by the Bureau), there is currently no work planned to combine all data sources (especially data from other agencies and the Bureau's subdaily gauge and radar data). It is suggested that these other sources of data be included in future rainfall products being developed through WIRADA.

It is also noted that the joint Bureau of Meteorology – CSIRO Centre for Australian Weather and Climate Research (CAWCR: see www.cawcr.gov.au) is undertaking research into assimilation of precipitation observations into their weather models, in addition to those observations currently used. The Australian Community Climate and Earth-System Simulator (ACCESS) is the model that will be used in future (not currently used operationally) for 'weather prediction and for diagnosing, analysing and forecasting Australia's climate sensitive natural resource systems (rainfall, soil water, vegetation)'. This model and the assimilation schemes used within therefore provide significant opportunity for use in terms of water balance estimation and should be considered for aspects of the water balance, where appropriate. Furthermore, one of the subprojects within the Strategic Radar Enhancement Project (SREP) is to undertake assimilation of radar reflectivities, with a 4-km gridded product being available hourly and being operational by ~2014–15 (Peter Steinle, CAWCR, pers. comm.). Given the overlapping research aims of our WIRADA colleagues and CAWCR, opportunities such as this for collaboration between WIRADA and CAWCR should be investigated more thoroughly in future.

Recommendation:

Two publicly available well tested methods are applicable for population of the precipitation terms within the water balance framework: the SILO and the BAWAP daily rainfall datasets. Given the similar performance of the two methods and the fact that the BAWAP method is produced within the Bureau, the BAWAP method is selected for use in subsequent analysis (although the SILO dataset will also be evaluated as input to water balance calculations to gauge the differences that may occur to such changes in input). It is noted that calculation of the uncertainty in the estimated interpolated daily rainfall surface is currently being supplied operationally within BAWAP only. Currently there is no method applicable for estimation of snow versus rainfall precipitation amount. However, the precipitation fields can be used in conjunction with temperature fields. For example, when the average daily temperature is above zero degrees centigrade the precipitation is rainfall; otherwise it is classed as snow. This method is proposed to be used to determine snow versus rainfall input to land surface.

3.2.2 Evapotranspiration

Evapotranspiration (ET) is a term used to describe the sum of evaporation and plant transpiration from the Earth's land surface to the atmosphere (Dingman, 1994), with approximately 90% of rainfall within Australia returning to the atmosphere through this process. Evapotranspiration is a required input into the water balance as a flux from the Landscape water store (Table 2 – evapotranspiration from landscape water store) and the Surface water store (Table 3 – evaporation from major and minor storages, private storages, natural surface water features, evaporation from rivers, evaporation from irrigation channels). ET data are also used as input into estimation methods for other components of the water balance (e.g. as input into rainfall–runoff models).

Actual Evapotranspiration (AET) is the ET that actually takes places in the landscape given actual moisture and energy conditions. AET is used to assess the volume of water lost to ET from the landscape, including from land used for different purposes. Potential Evaporation (PE), in this review, refers specifically to the evaporation from open waterbodies. Potential evapotranspiration (PET) is the evapotranspiration that would occur with an unlimited water supply. PET is not used directly in the water balance calculations, but it is used as a model input for rainfall–runoff models for runoff estimation.

There are various directly measured and derived estimates available for AET, PET and PE. The Bureau collects Class A pan measurements of PE at approximately 270 currently operating stations Australia-wide, whereas total daily evaporation from Class A evaporation pan measurements is also scheduled to be supplied by water agencies as part of the Water Regulations (see 4d in Appendix A). There are also seven flux towers that have provided local estimates of water vapour flux (hence AET) through eddy covariance methods over various periods since 2001 (Guerschman et al., 2009). Given the sparsity of AET observational data, AET is often estimated from measured values and other meteorological input fields with a greater density of observation (through the use of associated meteorologically and/or empirically based equations – see methods discussed below) and/or through remotely sensed observations (see Kalma et al., 2008 for a review of methods for using satellite data for evaporation estimation). See the sections below for a detailed description of the data and estimation methods currently available for Australia.

Evaporation from open water (PE)

There are several national PE datasets available for Australia that could be used for the estimation of evaporation from open water. The Bureau has produced gridded average monthly and annual PE estimates based on interpolated pan data for the period 1975–2005 using 270 stations (BoM, 2008; Mills et al., 1997). These datasets are climatological average values, i.e. single average gridded values for the entire time span. They do not represent daily, monthly or annual variability and are therefore not considered ideal for water balance calculations and WRA.

The Queensland Department of Natural Resources and Water (DNRW) has produced two surfaces as part of the SILO dataset: the first is based on interpolated daily measurements at the Bureau's 270 pan sites available post 1970, and the second is a synthetic method based on an empirical model with other interpolated climatological variables (Rayner, 2005), thus incorporating information from many other sites. Notably, the DNRW synthetic methodology does not incorporate effects due to wind and does not replicate trends in observed pan evaporation (possibly because of the temporally stationary empirical relationships used, or other variables not incorporated within the empirical relationship). If the interpolated Class A pan evaporation data were used to estimate open water evaporation a pan coefficient would need to be applied, as pan evaporation is greater than that from natural, open waterbodies.

CSIRO Land and Water have also recently produced a series of national gridded evaporation datasets on a daily time-step for the period 1981–2006 (Donohue et al.,

2009). The two most appropriate methods in their comparison are those based on the Penman and Penpan models, which include recent national windspeed data in their estimation (McVicar et al., 2008).

The method used in the estimation of open water evaporation within the MDBSY project combined mass transfer and energy budget principles in a single equation (with SILO climate data used as input) (McJannet et al., 2008). The Penman-Monteith method was used, with an adjustment to the amount of energy available for evaporation on the basis of changes in heat storage within the water-body (McJannet et al., 2008). Waterbody width and depth (as required for open-water evaporation estimation) were estimated differently for irrigation channels, streams and reservoirs, as detailed by Kirby et al. (2008); see Appendix B.3.1 for further details.

The most recent AWAP output (26z) provided a PE estimate appropriate for calculating evaporation from open water. It is available on a 0.05° (~5-km) grid for the period from January 1980 to June 2009 and is a Penman estimate of point PE. It represents the evaporation that would occur from a small open-waterbody and assumes that evaporation does not modify the meteorology through evaporative cooling. It assumes aerodynamic conductance of 0.01 m/s, and the saturation deficit is estimated as (saturation vapour pressure at maximum daily temperature) – (saturation vapour pressure at minimum daily temperature).

Evapotranspiration from the landscape (AET)

The Bureau, jointly with CRCCH (Wang et al., 2001: related to the average PET estimates), has published 0.1° (~10-km) gridded average monthly and annual AET estimates. Like the Bureau's PE estimates, these are climatological averages and are not considered adequate for WRA. Within Water2010 (and subsequently to provide contextual information for AWR 2005), gridded monthly and annual AET estimates were provided on the basis of a steady state annual/monthly model relating AET to water storage, precipitation and potential evapotranspiration. More recently, a national 0.05° (~5-km) daily gridded AET dataset has been produced as part of the WaterDyn column water balance model used within AWAP (Raupach et al., 2008): see Appendix B.5.2. The AWAP AET estimate incorporates remotely sensed vegetation cover, but it is a monthly 'climatological' average (i.e. a single grid to represent all Januaries) and does not capture land use change from year-to-year. WaterDyn is a water balance model and therefore has the advantage of internal consistency if used to estimate other water balance terms. The disadvantage of this model is that the water inputs in any grid cell are confined to precipitation alone and therefore do not include water added to the landscape through irrigation, lateral flow or groundwater interaction.

AET estimates were produced on a 0.01° (~1-km) national grid within the MDBSY project by using remote-sensing methods (Guerschman et al., 2008). This dataset was based on a combination of AET estimates from a) high-resolution satellite temperature measurements for 1990–1999, and b) satellite measured greenness and soil wetness for 2000–2006 (see Appendix B.5.3 for further details). The 2000–2006 portion of the dataset uses monthly values of the Enhanced Vegetation Index (EVI) and the Global Vegetation Moisture Index (GVMI) derived from the MODIS-Terra data to calculate vegetation greenness and moisture availability in the canopy and at the surface. It combines these indexes with gridded monthly estimates of Priestly-Taylor reference ET and precipitation (Guerschman et al., 2009). The AET calculated includes evaporation from soil and surface water, plant transpiration, and evaporation from intercepted precipitation. This method is calibrated by using flux tower measurements but is not physically limited by water balance calculations. It does not assume that precipitation is the only input to each grid cell and thus does allow for the input of water from irrigation, lateral flow and groundwater interaction.

It is noted that a comparison of the currently available national gridded AET estimation methodologies is planned as part of the WIRADA Precipitation and Actual

Evapotranspiration project (Renzullo and King, 2008) to be finalised in June 2010, with a pilot operational system to be implemented within the Bureau by December 2010. The methods being considered for inclusion in the comparison study are listed in Table 6. A prototype system, incorporating multiple constraint estimation, is to be implemented by January 2012. As the pilot operational system/methods will not be available for the first scheduled prototype water balance, the following recommendations are made on the basis of this review and the availability of national datasets.

Table 6. Summary of possible algorithms for inter-comparison and evaluation (reproduced from King, 2009). See Appendix B for further details of these methods.

Method	Proponent (Organisation)
NDTI	McVicar et al. (CSIRO Land and Water – CLW)
MODIS ETp scaling	Guerschman *et al.* (CLW)
AWAP	Raupach *et al.* (CSIRO Marine and Atmospheric Research – CMAR)
MODIS surface conductance – continental	Leuning/Zhang *et al.* (CMAR)
MODIS surface conductance – global	Mu *et al.*
SEBAL Regional	Bastiaansen *et al.* (WaterWatch)
CABLE	ACCESS – (CAWCR – the joint research program of BoM/CMAR).
LPJml	Bondeau *et al.*
BoM LAPS	BoM
ERA-40 reanalysis	The European Centre for Medium-Range Weather Forecasts (ECMWF)
Geostationary satellite	McCabe (University of New South Wales)

Potential evapotranspiration estimates for input to models (PET)

The Bureau has published (through research undertaken as part of the Cooperative Research Centre for Catchment Hydrology – herein 'CRCCH') 0.1° (~10-km) gridded average monthly and annual PET climatological estimates. These PET estimates were based on Morton's (1983) complementary relationship using 713 station measurements of temperature, vapour pressure and solar global radiation interpolated for the period 1961–1991 (Wang et al., 2001). The scenario modelling undertaken within the MDBSY project also used the above Morton's wet environment evapotranspiration algorithms to estimate PET but used the DNRW-SILO daily climate surfaces instead of the station measurements (CSIRO, 2007).

There are several national datasets that use the FAO56 method of producing a reference evapotranspiration (Allen et al., 1998). This method applies the Penman-Monteith equation, drawing on the FAO-recommended default values to varying degrees. DNRW-SILO have produced a national gridded PET dataset using this method and the climatological default values for wind suggested in the FAO56 guidelines. Donohue et al. (2009) from CSIRO has also produced a national FAO56 evapotranspiration dataset for 1981–2006, but it included the daily wind data produced by McVicar et al. (2008) instead of the default values.

The PET that is used to calculate the AET in WaterDyn is available on the same national grid. It is calculated by the Priestly-Taylor equation and is therefore not considered ideal for open water evaporation, but it could be used as input into the modelling of other terms such as runoff through rainfall–runoff modelling.

Recommendation:

Evaporation from open water (PE)

It is the recommendation of this review that in the short term the Penman-based point PE estimates from AWAP (26z) be used to estimate evaporation from open waterbodies. These datasets are available on the same 0.05° (~5-km) grid as the Bureau's climate and other AWAP datasets and at a daily time-step covering the period required for the Water Balance/Accounts methods pilots.

In the long term it is recommended that a heat storage term be included in the calculations, as was done in the MDBSY project. This is not recommended until a national detailed waterbody characteristics dataset is available, as there is potential to introduce error where these datasets are not complete.

Evapotranspiration from the landscape (AET)

It is the recommendation of this review that both the AWAP- and MDBSY MODIS-based AET estimates be trialled in the short term for comparison in the context of the Bureau's water balance framework.

Both of these AET estimates are good options, for different reasons, for use in the water balance calculations. The AWAP AET represents the opportunity for internal consistency with other major water balance terms (e.g. soil moisture and runoff) but does not represent additional water inputs to the landscape, such as irrigation, lateral flow and groundwater interaction. The climatological nature of the vegetation cover input also assumes no change in land use or irrigation regimes. The MDBSY MODIS-based AET has the advantage of representing additional inputs of water to the landscape, including irrigation, lateral flow and groundwater interaction, which feature in the water balance framework. It is also available on a finer grid scale and therefore has the potential to spatially distribute AET in irrigation areas for the assessment or water use patterns. On the other hand, it is not currently consistent with the other major terms of the water balance and could therefore result in large errors in closing the water balances, primarily because of the sheer magnitude of AET in the context of many of the water balance terms.

Recommendations for the long term will depend on the results of comparisons in the methods pilots and the WIRADA Precipitation and Actual Evapotranspiration project (Renzullo and King, 2008).

3.3 Landscape water storage and fluxes

3.3.1 Snow (storage)

Precipitation (discussed in section 3.2.1) that falls to the Earth's surface as snow, if kept in a solid state, can form a significant water storage component over months in some locations. This is released as runoff, evapotranspiration and groundwater recharge (among other processes) once melted. Therefore, this storage term is considered within the water balance framework as a component of the Landscape water store (Table 1).

Regular snowfall in Australia occurs only in the alpine regions of Tasmania, north-east Victoria, southern NSW and the ACT during winter and early spring. The timing, duration and intensity of the snow season can vary considerably from year to year (Davis, 1998).

In the Bureau's ADAM database, snow is recorded as rainfall, either via melting frozen precipitation measured in a rain gauge or via a 203-mm snow gauge. These measurements tend to have a high degree of error associated with them because of local site conditions. For example, the Falls Creek Automatic Weather Station has been estimated to underestimate by 50% to 70% (pers. comm., Blair Trewin, National Climate Centre). Snow depth measurements are undertaken by Snowy Hydro Limited at Spencers

Creek, Three Mile Dam and Deep Creek, but this information is not sufficient to estimate depth over the alpine region.

Although the distribution and depth of snow cover is dependent mainly on elevation and air temperature, other factors such as latitude, slope, wind exposure and vegetation mean that a simple calculation of snow volume based on elevation and air temperature is too crude to provide a reasonable estimate of snow water volume (pers. comm., David Walland, Executive and International Affairs Branch, Bureau of Meteorology).

Snow mass can be estimated from snow depth and extent information, then converted to equivalent water volume by using a snow density factor (e.g. an average value of 0.4 was used by Hennessy et al. (2003); remotely sensed hyperspectral data have been used to estimate density to a limited depth (pers. comm., Chee Yin Lee, Centre for Remote Sensing and Photogrammetry, RMIT). Given the paucity of observations in the Australian Alpine region, alternative sources of snow depth, coverage and water-equivalent data include satellite products and snow model output. Snow cover can be estimated at the regional and catchment scale by using remote-sensing techniques (Tampellini et al., 2003). Remote sensing coupled with land surface modelling can be used to estimate snow mass (Niu et al., 2007). Models for the Australian Alpine region have been developed for climate change and scenario modelling. These include the CSIRO (Whetton et al., 1996) and Melbourne University snow models. Gridded products such as those generated from MODIS Terra /Aqua and NOAA satellite data are available at a range of spatial and temporal scales and varying accuracies. Hall and Riggs (2007) indicate that accuracy is reduced in forested, complex terrain and ephemeral snow areas (such as those typically found in Australia). In addition to this, a new technique to estimate snow water content has been developed at RMIT; it uses high resolution imagery to model ground and snow terrain and hyperspectral data to determine snow depth (pers. comm., Chee Yin Lee, Centre for Remote Sensing and Photogrammetry, RMIT). However, the direct use of this method is restricted by the availability of good quality aerial photography in the alpine region at the required times. It is noted that national snowpack analysis is currently undertaken by the United States National Weather Service (www.nohrsc.noaa.gov/nsa/), which uses assimilation of remotely sensed data and measurements of climatological data. However, such products (in near-real time and reanalysis mode) are not currently produced at sufficiently small spatial scale within Australia for use in water balance modelling estimation.

Despite the potential availability of snow water content data, these products are difficult to validate due to limited good quality observations in the region and the uncertainty may be too great given that a change in snow store is not expected to have a significant influence on the water balance for most catchments. In AWR2005, change in the snow component was not quantified.

Recommendation:

It is recommended that, for the initial water balance, snow storage not be considered. However, this component could potentially be populated in the future as efficient techniques for deriving estimates become accessible.

3.3.2 Interception (storage)

The process of interception of rain on vegetated land surfaces is well documented elsewhere (e.g. Brutsaert, 2005; Ladson, 2008). Other interception processes may include 'land surface roughness' (e.g. capacity for impervious rock surfaces to hold rainwater) and interception by impervious surfaces in an urban environment.

Although these processes are known to occur, it is not thought that they would be explicitly considered in the first few years of estimating catchment water balance. The water held in these stores is mostly evaporated during the period 1 or 2 days after an event and is often indistinguishable from plant transpiration and surface evaporation. The rate of plant transpiration can be reduced by evaporation from interception stores as a result of humidification of the air in the vegetation canopy air space.

Recommendation:

It is recommended that interception storage be treated as equal to zero for the purpose of the pilot water balance studies. Incorporation of interception should be investigated within WIRADA.

3.3.3 Water in upland storage (swamps, depressions, streams not defined as part of the Surface water store) (storage)

In upland areas there may be a significant portion of land surface runoff that is held in swamps, landscape depressions, small natural lakes and riverbeds (above the point at which a river becomes part of the Surface water store; this might be the uppermost river gauge on a tributary river). Also, there may be an overlap in the definitions of interception (section 3.3.2) and water in upland storage (this subsection).

The water balance of natural upland waterbodies may behave similarly to water stored in small stock and domestic farm dams, providing a source of water for stock in grazed areas and/or non domestic animals in forested areas.

Recommendation:

It is recommended for the pilot studies that no attempt be made to separate upland waterbodies (discernable on currently available spatial data) that are likely small farm dams from those that are natural features with regards to water balance modelling.

3.3.4 Soil moisture – unsaturated zone (storage)

Soil moisture storage within the unsaturated zone is, for the purposes of the water balance framework, a component of the conceptual Landscape water store (Table 1). This component describes the moisture content (often expressed as a relative wetness or total volume) for a given soil volume.

Soil moisture is measured in situ by a variety of techniques. However, because of the spatial variability of soil moisture and sparsity of measurements, such methods cannot be used directly for the purpose of large-scale soil moisture estimation. It is noted that there is currently no provision in the Water Regulation data for soil moisture measurements (Appendix A). As ground-based measurement methodologies cannot be applied, remotely sensed satellite soil-moisture estimates, water balance modelling and assimilation of such remotely sensed (and other climatological observation) data into models are typically employed to estimate soil moisture.

An example of a soil moisture estimate produced globally/nationally using assimilation of remotely sensed data and other derived climatological fields is the Global Land Data Assimilation System (GLDAS) project (Rodell et al., 2004), and subsequent refined

applications in specific areas/continents. These systems can be used to derive soil moisture estimates by input into hydrological models: see http://hydrology.princeton.edu/~luo/research/FORECAST/current.php for an estimate of soil moisture across the continental USA. Various satellites have also produced associated soil moisture estimates, with WindSat/ASCAT and ASAR producing soil moisture estimates at 25-km and 1-km grid resolutions, respectively (pers. comm., Adam Smith, BoM). However, these estimates are not currently output on a consistent national basis, as is required for soil moisture accounting for catchments within Australia. That said, the work of Draper et al. (2009) validates the use of AMSR-E satellite retrieval algorithms for estimation of near-surface soil moisture at 0.25° (~25-km) spatial resolution for a set of sites over the Murrumbidgee and found high correlations between observed and estimated near-surface soil moisture.

Apart from the satellite-derived methodologies for soil moisture estimation, water balance models (of varying sophistication) are sometimes employed that use only forcing climatological fields, such as rainfall and temperature, as inputs. These models typically have conceptual soil moisture store(s) from which runoff and deep drainage are generated, depending on the forcing input. Spatially varying soil properties are typically also required as input to such models. Two models currently produce national soil moisture estimates on a 5-km grid: i) the WaterDyn model used within AWAP (Raupach et al., 2008, see www.csiro.au/awap), and ii) AussieGRASS (see http://www.longpaddock.qld.gov.au/AboutUs/ResearchProjects/AussieGRASS/index.html). AussieGRASS was developed specifically for grazing lands and is therefore considered inadequate for the wider variety of vegetation within Australia. Furthermore, the CLASS-u3m-1d model (Tuteja et al., 2004), coupled with forcing climatological data and Australian soil properties (McKenzie et al., 2000) can also be used to estimate soil moisture. The AWAP (WaterDyn) methodology was used as part of the AWR2005.

It is noted that soil moisture estimation techniques and evaluation are a part of ongoing research within the Bureau (CAWCR) and also under the WIRADA WRAA project. In particular, the use of remotely sensed observations for estimation of soil moisture and use in hydrological models is a focus area of research (Gouweleeuw et al., 2009; Liu et al., 2009a; Liu et al., 2009b).

Recommendation:

It is recommended that, for the purposes of the initial pilot studies, the soil moisture estimates produced through AWAP be used for population of the water balance framework. Other methodologies (e.g. those using satellite data) were not considered to be at a sufficiently tested state. The AWAP methodology was chosen, as it has national coverage and can therefore be applied easily to the pilot study regions. Furthermore, an operational version of the AWAP water balance model (the WaterDyn model), identical to that being run within CSIRO, is currently being transferred to the Bureau.

3.3.5 Flux terms to the Landscape water store

The following flux terms are discussed in the sections of the report relating to the storage from which they originate:

- precipitation (from outside the subcatchment) – section 3.2.1
- snow (from outside the subcatchment) - section 3.2.1
- leakage/seepage from private storages (from Surface water store) – section 3.5.4
- capillary rise (from Groundwater store) - section 3.5.5
- water use – rural irrigation (from Water transport system) – section 3.6.10
- water use – urban irrigation outdoor (from Water transport system) – section 3.6.11
- wastewater/recycled water for irrigation (from Water transport system) – section 3.6.12
- seepage from septic tanks (from Water transport system) – section 3.6.13
- water transport system leakages (rural/urban) (from Water transport system) – section 3.6.14
- seepage from irrigation channels (from Water transport system) – section 3.6.15.

3.3.6 Evapotranspiration (flux: exiting subcatchment)

Evapotranspiration from the Landscape water store is accounted for in the water balance framework in Table 1. As evaporation from open water is accounted for in other terms in the water balance framework, evapotranspiration from the Landscape water store represents the actual evapotranspiration from the catchment area, excluding the areas of open water. See Section 3.2.2 for the available and recommended methods for estimating actual evapotranspiration from the landscape.

3.3.7 Runoff (flux: to Surface water store)

Runoff from the landscape water store is accounted for in the water balance framework in Table 2. In the context of the water balance framework, runoff is defined as the accumulated runoff, comprising surface runoff and/or runoff from the subsurface soil layer. Surface runoff occurs when the surface soil layer becomes saturated or when the rainfall intensity (or irrigation intensity) exceeds the infiltration capacity of the soil. Within the defined water balance framework, runoff from the land (and impervious surfaces such as roofs) then flows into surface water features (see Table 3) including:

- creeks and rivers
- natural surface water features (e.g. wetlands)
- major and minor storages
- private storages: farm dams and rainwater tanks.

As long as the method for calculation of runoff allows the estimation of the amount of runoff that goes to each of these storage terms, the method satisfies the requirements as specified by the detailed water balance framework.

As local measurement of runoff is not currently available, except through indirect measurement of runoff using aggregated streamflow measurements, catchment runoff estimates are generally obtained from hydrological models. A large number of catchment models have been developed and applied both in Australia and internationally for estimating surface runoff. Models vary according to their specification of processes and

spatial and temporal resolution (Viney, 2008) and may have been developed for a particular purpose such as flood forecasting, water balance modelling and sediment transport modelling. Descriptions of model types and a summary of some of the more widely used models are provided in Appendix C.

The models reviewed below have been deemed to be the most relevant existing approaches on the basis of the following considerations:

- previous successful application of the model on a large scale
- suitability for a range of catchment characteristics (including urban)
- complexity appropriate for the temporal and spatial scales
- availability of data to meet the model requirements
- ability to apply and run catchment models at national scale within the required time frame.

For unimpaired catchments where there has been negligible water resource development and where the time periods allow for delays in transmission, runoff can be obtained from observed stream gauge data. CSIRO Land and Water (Dr Francis Chiew) has defined 200 gauged catchments across Australia that can generally be classified as unimpaired catchments. These are a modified version of the unimpaired catchments defined by Peel et al. (2000) for the National Land and Water Resources Audit. The observed outflows from these catchments have been used to test modelled catchment runoff, as described below.

SIMHYD, Sacramento and SMAR

SIMHYD is a seven-parameter lumped conceptual rainfall–runoff model that estimates daily streamflow from daily rainfall and areal potential evapotranspiration data. SIMHYD is one of the rainfall–runoff models available within the eWater Catchment Modelling Toolkit. The model is suitable for urban catchments and, in a modified form, is incorporated into MUSIC, which is used for urban stormwater modelling.

SIMHYD was used in the National Land and Water Audit (Peel et al., 2000) and has recently been applied to the whole Murray Darling Basin area for the Sustainable Yields project. The model will also be used in the southwest Western Australian, northern Australian and Tasmanian regions under the extension of the same project (Chiew et al., 2008). The adopted method is referred to as a spatialised lumped model, as some spatial variation is incorporated through the use of gridded (0.05° x 0.05°) daily rainfall and evapotranspiration data. The Muskingum routing method is used to route the runoff from each cell. Comparison of modelled runoff against observed monthly stream gauge data for 183 unimpaired catchments in the Murray Darling Basin indicates that SIMHYD performs reasonably well for unimpaired catchments using nearest-neighbour catchments for parameter regionalisation (Chiew et al., 2008), although that report did not validate the regionalisation used for extrapolation to impaired catchments. Also, a comparison of model results suggests that the more highly parameterized Sacramento model has only a slightly better performance.

Six of the model parameters need to be optimised through calibration against observed streamflow data. Therefore, application of the model to ungauged catchments requires some kind of regionalisation approach to parameterisation. Methods include using default parameters, application of the parameters from the nearest gauged catchment, and using parameters from the most similar catchments, as determined by a similarity index (Chiew et al., 2008; Post et al., 2005). Measures that have previously been used to assess catchment similarity have included area, elevation, slope, stream density and mean annual rainfall (Post et al., 2005). There has been some testing of these approaches (Post et al., 2005), but Viney (2008) has identified this as an area of potential improvement in model accuracy. This may include using an ensemble approach where parameters from

several of the nearest gauged catchments are used to reduce the uncertainty of the estimated runoff. However, the use of multi-donor catchments with SIMHYD will work only if the characteristics of the selected catchments result in flows on both sides of the required flow. In other words, the flow ensemble should contain the true or the desired value. If not, there will always be a bias and this will be larger larger than for the best model in the selected donors.

A range of other relatively simple conceptual models have also been applied within several of the Sustainable Yields studies being undertaken. Two models in particular (Sacramento and SMAR) provide sufficiently distinct conceptualisations compared with SIMHYD and have been incorporated into the modelling toolkit, and regionalisation studies have been undertaken. If rainfall–runoff models are to be applied within the pilot studies, some comparison with other conceptual runoff models would be beneficial. As some models perform better in differing regions, some form of model blending may produce better estimates of runoff. Therefore, if SIMHYD is applied, it is suggested that these two rainfall–runoff models also be applied for comparison purposes.

WaterDyn

WaterDyn is a fully dynamic two-store water balance model, developed for the Australian Water Availability Project (AWAP) (Raupach et al., 2008). The model requires meteorological forcing data in the form of gridded precipitation, solar irradiance, and maximum and minimum air temperatures. Monthly Australia-wide 0.05° gridded runoff data are available in near-real time as operational products on the AWAP website (http://www.csiro.au/awap/), and historical data are available on a monthly basis from 1900.

Runoff entering streamflow is modelled as two components: surface runoff and deep drainage. Surface runoff occurs only when the upper soil layer is saturated and is then equal to the rate of precipitation. Deep drainage is a function of the relative soil moisture and the saturated hydraulic conductivity of the soil layer. Catchment runoff can then be derived by calculating the average surface runoff and deep drainage for all grid cells in a catchment and summing them together for the whole catchment area. A low-pass filter can be used to incorporate a transmission delay in both components. For unimpaired catchments, the total should be equal to the observed catchment outflow.

Raupach et al. (2008) undertook testing to compare modelled catchment outflows with observed catchment outflows on long-term, monthly and daily time scales for the 200 unimpaired catchments identified for the Sustainable Yields project. The results indicate that, for annual and monthly outflows, the model produces reasonable results without apparent bias. The exception to this was a tendency to slightly overestimate runoff in dry catchments.

The current WaterDyn model does not allow for data assimilation with observed streamflow, but this is a future goal for the model (Raupach et al., 2008).

There are several areas of no data in the current model output that correspond to lakes and saltpans for which no soil parameter data is available. These areas are unlikely to have a significant impact on catchment runoff.

TOPKAPI

The TOPKAPI model is a grid-based simulation approach based on the idea of combining the kinematic approach with the topography of the catchment described by a DEM. It is a rainfall–runoff model in which few parameters are estimated by using calibration procedures; instead, they are inferred a priori from spatially varying characteristics deterministically (Liu et al., 2008). TOPKAPI requires spatial elevation, soil, vegetation and land-use data (Ciarapica and Todini, 2002), which are currently available Australia-wide. If flow data are available, some fine tuning can be done on some of the parameters (pers. comm., Todini). TOPKAPI has the practical advantage that the model parameters can be

obtained from the physical characteristics of the catchment and the model does not, in general, need calibration. It is noted that this does not necessarily imply that parameterisation of the catchment is superior to that with other models using catchment-based calibration.

TOPKAPI has been applied with success to catchments in Europe and China (Liu et al., 2008) and, more recently, in South Africa (pers. comm., Geoffrey Pegram, University of KwaZulu-Natal). The model has most commonly been used for the purposes of flood forecasting, and therefore most of the published results relate to performance compared with rainfall events rather than on longer time scales.

WaterCAST and CWYET

The Water and Contaminant Analysis and Simulation Tool (WaterCAST, see www.ewatercrc.com.au/downloads/technologies/P5.pdf and www.toolkit.net.au/Tools/E2) is a modelling tool being produced by the eWater CRC with the aim of higher level adoption across the Australian water industry. The purpose of WaterCAST is to provide managers with the capability to make informed decisions as to how changes in catchment management affect the quantity and quality of runoff to receiving waters. Unlike other catchment models, WaterCAST does not have a fixed structure, but rather requires users to select a combination of models best suited to the problem. Models created with WaterCAST will be able to predict the hydrological behaviour of catchments of sizes varying from backyards to basins, made up of tens to hundreds of sub-catchments. The model structure is node-link whereby sub-catchment water and constituent fluxes are fed into nodes and are then routed along links. Sub-catchment processes consist of runoff generation, constituent generation and filtering. Along the links, routing and instream processing take place. Spatial data on elevation, land use and management, climate, geology, and soil data are used.

Sub-catchments are divided into similar areas (functional units) with common responses or behaviours on the basis of land use/cover, management, or position in landscape. A node is a point where sub-catchment water and constituents enter or leave or where there is a confluence. Links serve to store water and route or process water and constituents passing from node to node. They also allow for interaction with the floodplain for links with large floodplain areas. Because of the conceptual similarity between links and storages, storages are viewed as short links instead of nodes.

WaterCAST has a system for associating uncertainty with model parameters and reporting parameter uncertainty across all models. The uncertainty is communicated by using a traffic light method. Each parameter is assigned a traffic light setting based on a two-part rating:

- the confidence in the values (red, amber or green)
- the sensitivity of the model output to that parameter (large, medium or small).

A sub-catchment can have a number of functional units (FUs), and each can be assigned a different rainfall–runoff model. Each WaterCAST link represents a stretch of river for which hydrologic routing is carried out.

It is also noted that CSIRO is developing the Catchment Water Yield Estimation Tool (CWYET) developed on behalf of the eWater CRC funded by the National Water Commission (pers. comm., Jai Vaze). CWYET will be delivered in June 2010 and will involve calibration of a range of rainfall–runoff models to approximately 300 catchments in Southern Australia. It will allow a range of regionalisation methods to produce runoff estimates for impaired catchments. The methods used in CWYET build upon the methods employed within the Sustainable Yield projects. Furthermore, the CWYET rainfall–runoff parameterisations are expected to form a set of standard parameters for input into WaterCAST. Given the overlap of areas over which the CWYET is to be applied (Eastern and Southern Australia) with the pilot regions, if simulations are available for this

methodology in time for the pilot studies, this methodology can be considered a contender for use within the 2009 pilot studies.

LUCICAT

The land-use-change incorporated catchment (LUCICAT) model is a semi-distributed conceptual catchment hydrology model developed to represent the effects of land-use and climate changes on streamflow and salinity generation processes (see Appendix C for details). The model divides a large catchment into a number of Response Units to take into account the spatial distribution of rainfall, pan evaporation, soil salt storage and land use. Each Response Unit forms a building block in the model and represents the physical processes of daily flow and salinity generation. The generated streamflow and salt load from each of the Response Units are routed by using a modified Muskingum-Cunge method. The model has seven physically meaningful parameters, most of which can be estimated a priori on the basis of spatially varying characteristics (e.g. soil type), with the remaining parameters requiring calibration.

The model runs in the LUCICAT Live framework, which includes GIS interface and data pre/post-processors (Bari et al., 2009a). The framework runs in a .NET environment and utilizes CSIRO's TIME (The Invisible Modelling Environment) components. The model has been applied to many catchments in Western Australia and can be classified into three groups: (i) land-use management (Beverly et al., 2005), (ii) yield prediction and (iii) climate change (Charles et al., 2007). This model has been applied to more than 10 high-priority catchments in Western Australia and is being used in the CSIRO's south-west Sustainable Yield Study (Bari et al., 2009b).

WIRADA

It is noted conceptual and semidistributed models and techniques are being developed as part of the WIRADA WRAA project. In particular, the following issues are being investigated/undertaken:

- conceptual model regionalisation and model weighting techniques (Li et al., 2009; Viney et al., 2009a; Viney et al., 2009b; Zhang et al., 2008; Zhang and Chiew, 2009)
- incorporation of remotely sensed soil moisture (Gouweleeuw et al., 2009; Liu et al., 2009a, 2009b), evapotranspiration (van Dijk et al., 2009; Zhang and Chiew, 2009; Zhang et al., 2009) and other variables (McVicar et al., 2009) into landsurface hydrology models
- benchmarking of landsurface water models (Viney, 2009). This task includes collation of a national benchmarking dataset consisting of daily streamflow records for a set of unimpaired catchments representing the range of conditions across Australia.

This research will not be available in time for application to the 2009 pilot studies, but it will be used in subsequent years following appropriate testing.

Discussion

Currently it is proposed that runoff in the water balance be separated into runoff into rivers, major storages, natural waterbodies and private storages, and therefore a distributed or spatialised model may facilitate the calculation of runoff for smaller subcatchments associated with these features. This also allows flexibility if reporting boundaries or areas of interest change in the future.

To generate catchment water balances Australia-wide within the required time-frame, the approach should be based on established methods. The MDBSY and AWAP projects provide recent examples of runoff modelled over regional scales. A comparison of AWAP and SIMHYD runoff estimates with observed monthly stream gauge data has been undertaken for the Murrumbidgee catchment pilot water balance (Daamen et al.,

Murrumbidgee pilot water balance, in prep.). The results indicate that both the AWAP and SIMHYD perform reasonably well in the upper Murrumbidgee area, with neither model consistently outperforming the other. It should be noted that this includes only catchments associated with high runoff areas, and a more comprehensive comparison would include catchments with a range of hydrological characteristics and different climate regimes. The models have been calibrated with data from headwater catchments. Thus the parameters from these catchments may not be appropriate for the catchments farther downstream unless there are similar catchments in the calibration set.

The MDBSY approach has the following shortcomings:

- SIMHYD parameters derived for the MDBSY project can be used initially for the catchments included in that project, but parameters for the remaining catchments in Australia would need to be determined by using an agreed regionalisation technique.
- Replicating and running the spatialised model within the Bureau may take several months and computational resources.
- Although gridded rainfall and runoff are used, the model is not distributed and a constant routing parameter is used for all cells in a catchment. Furthermore, the benefits of the spatialised nature of the model have not been shown as yet.
- Post et al. (2008) found that calibration of the model was very sensitive to the type of input rainfall. They therefore recommended that future development of rainfall–runoff models be focused on physically based dynamic models that do not require calibration (although these results also highlight the fact that higher quality rainfall inputs may provide significant improvements in such conceptual modelling).

The main advantage of the WaterDyn model is that it is already operational and being applied at the national scale. As currently used, the AWAP WaterDyn model has the following limitations:

- No routing method is applied in the model (it is a column model with no lateral transfer). Surface runoff and deep drainage for all cells in a catchment are assumed to have the same transmission time to the catchment outlet without a proper routing method.
- For production of an overall estimate of runoff (as defined by the framework), an assumption is made that all deep drainage discharges to streamflow; this assumption is used in the streamflow validation presented by Raupach et al. (2008). Although this might be reasonable in the headwater catchments, not all deep recharge will end up in streams or rivers in downstream catchments. This may require some method of distributing deep drainage into the streamflow and groundwater recharge components for those areas.
- Impervious surfaces and surface waterbodies are currently not represented within WaterDyn. Therefore, the model may not perform well for urban catchments or for situations where waterbodies cover a fraction of the grid cells (modelling is not undertaken for grid cells where the majority of the cell is a waterbody).

A fully distributed model such as TOPKAPI, for which spatial input data are available, may provide an approach that could be applied nationally. Although TOPKAPI has had promising results in other regions, there is currently a lack of expertise in Australia to proficiently apply the model on a large scale. The time required to develop these skills would affect the ability to meet the timeline for delivery of the water balance. Also, it may be desirable to use or adapt models developed within the eWater CRC, such as WaterCAST, so as to facilitate input of jurisdictional models (developed in WaterCAST).

Rainfall–runoff modelling is, and will be, undertaken in other areas of the Bureau, including in Flood Forecasting and Extended Hydrological Prediction. The LUCICAT model

is being trialled over a single catchment for this purpose in the Thomson catchment near Melbourne (pers. comm., Mohammed Bari) and has been applied previously to priority catchments within Western Australia – in particular within the South West Western Australia Sustainable Yields Study. This methodology was considered to take greater amounts of resources to implement for the purpose of the pilot studies than the other available methods, and it has not yet been shown to produce superior results to the other available methods. LUCICAT was therefore not considered further for application in the 2009 pilot studies, but it will be considered in future once benchmarking studies have been established.

Any approaches adopted in the future should take into account potential consistencies and efficient use of resources in rainfall–runoff modelling and the development of operational environments. For example, CABLE (CSIRO Atmosphere Biosphere Land Exchange) is the land surface module for the climate and Earth system model ACCESS currently being developed by the CSIRO and the Bureau. Some testing of the CABLE model has been undertaken within the WaterDyn framework (Raupach et al., 2008). The results indicated that CABLE has a bias towards overestimation of catchment outflows; this bias has been attributed to the underestimation of evapotranspiration. However, it is expected that the results will improve over the coming years given the thorough research and development of CABLE.

Recommendation:

It is recommended that:

- in the short term, the WaterDyn model be used to derive runoff estimates given:
  - the similarity in the runoff results of the SIMHYD and WaterDyn models using initial tests
  - the fact that the WaterDyn model is already operational nationally
- if practicable, the pilot studies runoff simulations be generated (using the methods developed within the Sustainable Yield Projects or CWYET) and compared with WaterDyn
- in the longer term, a benchmarking comparison of currently available methods for runoff generation (currently planned as part of WIRADA) be undertaken for WRAA purposes. TOPKAPI, LUCICAT, WaterDyn and AWRAM should also be reviewed in the future as more expertise in the use of this model is developed in Australia.
- where possible, consistent approaches to modelling and use of resources be adopted within the Bureau as a whole.

3.3.8 Interflow (flux: to Surface water store)

'Interflow' is the name given to any lateral flow of water that might occur between the land surface and the watertable. Interflow occurs at an elevation between the two other forms of lateral flow: above or on the surface, lateral flow is considered to be 'runoff', and beneath the watertable lateral flow is considered to be groundwater flow. Interflow may include saturated and unsaturated flow down hillslopes on soil or rock horizons with contrasts in hydraulic properties, as well as lateral movement of water in perched watertables.

Typically, interflow will be a significant flux only over a short lateral distance (<5 km). There may be increased evapotranspiration as a result of the interflow process: for example, deep-rooted vegetation can intercept interflow at the foot of a hillslope (break of slope).

Recommendation:

It is considered unnecessary to include an explicit representation of interflow in a catchment water balance. Interflow is usually accounted for in other terms like river flow (which includes land surface runoff, interflow and groundwater discharge/baseflow), evapotranspiration and groundwater flow.

3.3.9 Recharge (flux: to Groundwater store)

Estimation of recharge to groundwater stores is discussed in Section 3.5.3.

3.4 Surface water storage and fluxes

3.4.1 Natural surface water features – wetlands (storage)

The definition of wetland used here is the same adopted by the Directory of Important Wetlands in Australia (DIWA), which is based on that used by the Ramsar Convention. Wetlands include swamps, marshes, billabongs, lakes, saltmarshes, mudflats, mangroves, coral reefs, fens, peatlands, or bodies of water – whether natural or artificial, permanent or temporary. Water within these areas can be static or flowing, fresh, brackish or saline (Environment Australia, 2001).

Within this broad definition, the wetland classification system used in the Directory identifies 40 different wetland types in three categories: A—Marine and Coastal Zone wetlands, B—Inland wetlands, and C—Human-made wetlands. For the purposes of the water balance framework calculation, only some of the wetlands defined in the directory will be assessed for storage. The Australian Wetlands Database is available online at:

http://www.environment.gov.au/water/publications/environmental/wetlands/database/index.html

The database, among other data, contains information on: location, area, elevation, wetland type, site description, physical features and hydrological features.

For some wetlands the water volumes will be provided directly through Water Regulation data (e.g. category 3a, b – see Appendix A). However, most often because of a lack of water level/storage data, the change in storage is calculated by using a water budget. Figure 8 is a schematic representation of a riverine wetland water budget. The main components are evaporation, transpiration, precipitation, groundwater flux (recharge-discharge), inflows from river, inflows from irrigation drainage, return flow to river, pumping and diversion.

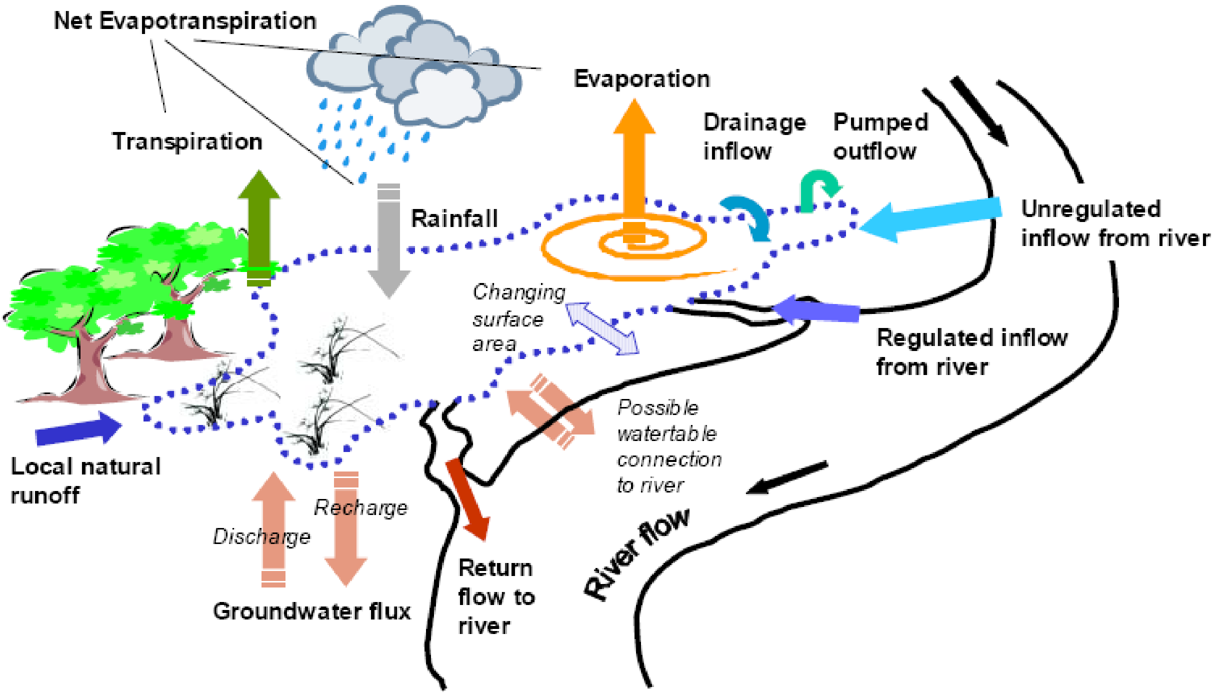

Figure 8 Schematic of riverine wetland budget. Diagram from Gippel (2005)

The water budget should be calculated at least on a monthly basis, and two approaches can be used: i) estimate the average monthly values of the water budget or ii) balance the water budget as a continuous time series, using long-term records. Gippel (2005) defined the water budget of a lake or wetland, over a specified time interval (t), as:

$$\Delta S(t) = [Qi - (Qo + Qp)] + [Gi - Go] + [A * (P - ET)] + e$$

where:

ΔS = change of water quantity stored in the waterbody (m^3)

Qi = surface water flowing into the waterbody (m^3) – see sections 3.3.7 (runoff) and 3.4.8 (streamflow) and Water Regulation data

Qo = surface water flowing out of the waterbody (m^3) – see section 3.4.8 and Water Regulation data

Qp = pumped extraction (m^3) – see sections 3.4.11 to 3.4.15 and Water Regulation data.

Gi= groundwater flowing into the waterbody (m^3) – see section 3.5.4

Go = seepage to groundwater (m^3) – see section 3.5.4

A = surface area of wetland (m^2) – estimate using satellite images where data are not available

P = precipitation falling on the waterbody (m) – see section 3.2.1

ET = evapotranspiration volume (m) – see section 3.2.2

e = error term

As Gippel (2005) suggested, the main problem in developing a water budget model lies in measuring or estimating the various components. Only a few studies have considered all components of the budget, and groundwater is particularly difficult to include.

A recent work on Barren Box Swamp located within the Murrumbidgee pilot catchment (Anderson et al., 2008) showed that loss to groundwater does not seem to occur at a significant rate. It was found that initial loss to soil moisture should be included in the

water budget, because when surface water level observations indicate that the wetland is dry, evapotranspiration may still be in progress. Furthermore, it is a volume of water that is 'lost' from the wetland and has to be replaced when the wetland refills. On the other hand, Kappen et al. (2004) showed that groundwater surface water interaction is very variable, even in nearby wetlands, and therefore fluxes from or to groundwater should be assessed carefully for each wetland type.

Kirby et al. (2008) provided independently verifiable modelled estimates of unmeasured water balance terms for wetlands and for floodplain water use and storage for the MDB. This included actual evapotranspiration from wetlands based on remote-sensing observation; reach and other open-water direct evaporation based on an energy balance method; and estimates of open water area. The evapotranspiration estimate was then used in a floodplain storage and water use model. Areas inundated by flooding were determined by the use of MODIS satellite imagery. This method also requires the assessment of volumes of water spilled during a flooding event and return flow to river.

Recommendation:

It is recommended that:

- in the short term, for the few pilot catchments, it may be possible to calculate wetland water balances by using the methodology developed in prior investigations (Anderson et al., 2008; Kirby et al., 2008) that have characterised the wetland.
- in the medium term, for the purpose of producing a national water balance, a very coarse estimate of the change in storage for major wetlands be undertaken using MODIS imagery to estimate changes in the area of open waterbodies, and possibly also using existing rating curves or spilled water volume estimates or DEM for storage calculations. In addition, actual evapotranspiration and direct evaporation should be used to evaluate the volumes lost through the atmosphere (see section 3.2.2). It is recognised that the proposed method, in contrast to that proposed by Kirby et al. (2008), does not take into account all components of a water balance, but only the change in storage and water lost to the atmosphere.
- in the long term, research under the WIRADA project be carried out in order to provide the Bureau with an appropriate methodology for assessing wetlands water budgets on a national scale. In particular, it would be very useful to extend the Kirby et al. (2008) methodology to other floodplain areas outside the MDB. In addition, other methods should be investigated for other types of wetlands such as coastal and groundwater dependent wetlands.

3.4.2 River channels, irrigation channels and urban drains (storage)

Gauge data are required to estimate the volume stored in rivers; therefore, the river store will be restricted to river reaches between gauges with reasonable data quality. This is similar to the approach adopted by Kirby et al. (2008) where reaches where restricted to those with good quality upstream and downstream gauge information for the purposes of creating a water account for the Murray Darling Basin. Although changes in the gauge network may occur, such as the inclusion of additional gauges, modification or decommission of existing gauges, or periods of missing records, the defined store should remain constant between reporting periods where possible.

Estimating the volume of water held in the surface water store with some level of accuracy would require detailed survey and monitoring. Although survey information may exist at some gauge locations and well studied areas, in general these data will not be available for most waterways. Whereas the length can be estimated from digital stream data (i.e. the AusHydro linear stream network), details of the width and depth are not generally known. As discussed by Kirby et al. (2008), channel metric methods for at-

station and downstream hydraulics relating channel width to channel depth and discharge have been developed. Relationships are dependent on site-specific characteristics and are generally derived from surveyed waterways in a region (e.g. DeRose et al., 2003; Stewardson et al., 2005). Although generally established for unregulated rivers, these equations allow a dynamic estimation of approximate volume in a section of river and rely on availability of gauge data at the end and start of a reporting period.

The steps in this approach are to:

- define the river store from the stream network data as the length between good quality gauges
- from the gauge data, estimate the width and depth of the stream at the gauge locations for the flow at the start and end of the reporting period by using applicable channel metric equations (e.g. Stewardson et al., 2005; Lawrence, 2007; Kirby et al., 2008)
- average the cross-sectional area of the stream at the upstream and downstream gauges and multiply by the length of the section to estimate volume
- where the section of river crosses a catchment or subcatchment boundary, apportion the volume linearly relative to the length of the section.

Storage in irrigation channels is dependent on the particular operating phase of the irrigation cycle, with the volume of water equivalent to the demand at any time plus an additional volume to account for distribution losses. Kirby et al. (2008) and McJannet et al. (2008) describe a method for using remote sensing to estimate width classes for irrigation channels and associated depths in the context of estimating evaporation. Although it may be possible to use these existing data to calculate irrigation channel volume in the Murray Darling Basin, this type of analysis may be too detailed and resource intensive for other areas, particularly as it may be difficult to determine the flow in the channels at a particular time.

Recommendation:

It is recommended that, for the defined surface store area, a channel metrics technique be used, as described above, to estimate the volume in river channels, and that the volume stored in irrigation channels be excluded from the balance for the initial pilots.

3.4.3 Major storages (storage)

Three further managed classes of surface water storage are considered within the water balance framework. These are:

1. major storages (maximum volume > 1 GL): provided by named persons within the Water Regulations
2. minor storages (100 ML < maximum volume < 1 GL): provided by named persons within the Water Regulations (amongst other conditions – see below)
3. private storages: all storages with a maximum volume less than 100 ML and those not named as major or minor storages (i.e. everything else).

The definitions align with the definitions used within the Water Regulations, with differing amounts of information associated with each class (more information is required for major storages, less for minor storages, and no information for private storages). As defined within the Water Regulations, certain organisations (named persons within the Water Regulations) are required to provide information on major and minor storages. Private storages are intended to capture the storage of water by individuals or private entities

that are not listed or storages that are exceptions within the Water Regulations (e.g. farm dams).

Major storages, for the purposes of the water balance framework calculation, are defined as large water storages (e.g. water supply dams) with a water storage capacity of 1 GL or more. Water volumes in major storages will be provided directly through Water Regulations data (category 3b – see Appendix A).

Recommendation:

It is recommended that Water Regulation data be used directly for major storage terms.

3.4.4 Minor storages (storage)

Minor storages are defined in the Water Regulations as any water storage in which water is stored for taking and that meets the following criteria: (a) it is not a major storage; (b) it has a storage capacity of 100 ML or more; (c) it is not used primarily for the precipitation of ash; (d) it is not a mine tailings dam; (e) it is not managed by an urban infrastructure operator primarily for the purposes of flood management or pollution abatement. Water volumes in minor storages will be provided directly through Water Regulations data (category 3e – see Appendix A).

Recommendation:

It is recommended that Water Regulation data be used directly for minor storage terms.

3.4.5 Private storages – farm dams, rainwater tanks, greywater and off-stream storage (storage)

Private storages consist of those managed storages that are neither defined as being major or minor storages. Thus, in line with the Water Regulations, all storages having a maximum volume less than 100 ML are considered private storages. There is also a range of exceptions to the minor (see above) and major storage classes. Certain persons (or organisations) defined as part of the Water Regulations do not have to supply data, even though the relevant storage may be above the minor (100 ML) or major (1 GL) threshold. Thus this storage is also considered a private storage to reflect the data availability. Private storage as defined here falls into several categories, including: farm dams, rainwater tanks, greywater, and off-stream storage.

The majority of private storage consists typically in rural areas of that in farm dams, whereas in urban areas rainwater tanks/greywater can form a significant storage within a subcatchment area. Furthermore, off-stream storage can also form a significant storage for irrigators (amongst others). Currently there are no data directly available on these types of storage. It is considered that, given the sparsity of data on rainwater tanks, greywater and off-stream storage, estimation of these terms should not be attempted for the 2009 pilot studies. However, such terms will be considered in future.

Given the high number of farm dams in rural areas, and the potential impact that these have on the overall storage and runoff that occur in a particular catchment, it is considered necessary to assess possible means of calculation of farm dam storage and impact on runoff. The remainder of the section focuses solely on farm dam storage. However, it is emphasised that other components of private storage will be included in future years.

Private storage in the form of farm dams is a component of the Surface water store, as defined in the water balance framework (Table 1). Farm dams have a significant impact in terms of the reduction of runoff that would otherwise become streamflow – see Appendix D.1 for a discussion of these impacts.

Existing private storage data

The Bureau is unlikely to receive data relating to storages operated by persons other than those listed in the Water Regulations (with the exception of static size and location information on storages that require a permit supplied under information subcategory 6e). Private storages are, therefore, those that are not operated by persons listed in the Water Regulations; they may be less than minor, minor, or even major, as defined under the Water Regulations. Double accounting of storages (where information is supplied under the Water Regulations but the storages are included in a separate modelling methodology) will be avoided by removing storages that have data supplied under the Water Regulations from the private storage modelling methodology.

Estimation of farm dam storage at any particular time is difficult, given the availability of related data. Data availability on private storages varies greatly between States and Territories and even between regions. Many private storages are not registered in government databases because they do not require a licence and/or were constructed at a time when they were not require to be licensed or referred to authorities. Current legislation in different States and Territories allows dams of a certain size or purpose to be constructed without licence or referral (Kollmorgen et al., 2007). The lack of information on the size (spatial extent and location), total volume of store (and/or periodical measurements of storage level), and associated water use of private storages presents obvious difficulties when attempting to account for the effects of private storages on the water balance. Furthermore, only a small proportion of private storages require official approval under State and Territory law; therefore, data supplied to the Bureau under subcategories 3e and 6e are likely to be relevant to only a small fraction of the total population of farm dams in Australia.

Possible methods for estimating the water balance components in private storages

Estimation of private storage must adhere to the framework proposed by Barratt (2008). Methods of estimating farm dam storage (or changes in farm dam storage over a given period) that have been applied within Australia are discussed in Appendix D.2. The most ideal methodology for estimating the change in storage in farm dams would be direct measurement via remote sensing. However, this is not viable on the temporal scale outlined in Section 2.5 (monthly or less). Therefore, estimation of water balance flux components (and thus, change in storages) is a viable alternative to measuring change in storage. Two potentially viable approaches exist for the calculation of the water flux components in farm dams for the purpose of application to pilot water balance studies:

- Use an existing methodology designed to model the impacts and water balance of farm dams, such as Sinclair Knights Merz's Tool for Estimating Dam Impact (TEDI) or Complex Hydrological Evaluation of the Assumptions in TEDI (CHEAT). This method calculates change in storage within farm dams across a catchment area as a whole (as opposed to calculation of storage levels directly at the start and end of the period over which the water balance is being calculated).
- Construct a private storage modelling methodology to estimate the farm dam storages directly that can be incorporated into a larger water balance methodology.

Whichever approach is taken, it is recommended that the water balance for private storages be accounted for in individual catchments before being combined into the national water balance (so as to account for catchment-to-catchment variability). It is proposed that the change in storage primarily be calculated via those water flux components that have the potential to be verified by less frequent measurements of changes in storage. By adhering to the concept of mass balance (Barratt, 2008), the change in storage can be reduced to the storage at the start of the reporting period plus the sum of the water flux component. The calculation of parameters described in the water balance is described for the two approaches in Appendix D.2.

CHEAT and TEDI and the flux terms required as input for use of these methodologies are discussed within Appendix D.3.1. One of the main advantages of using TEDI on a large scale is that it is a lumped model that allows known data to be extrapolated to areas where there are insufficient data. The simplicity of a non-spatially explicit model allows application to areas that are data sparse. TEDI also considers the majority of flow components involved with the management of farm dams. Previous Australian water balance reports that have included farm dam components include the AWR 2005 and the Murray-Darling Sustainable Yields (MDBSY) project. Only 11 of the 52 water balances compiled as part of the AWR 2005 report included opening and closing water storage balance (Kollmorgen et al., 2007). Closer inspection of the water balances included in the appendix of Kollmorgen et al. (2007) reveals that the farm dam water balance figures were merely reported as total volume, with no change throughout the water year. The MDBSY project attempted to quantify the effects on catchment yield of farm dam development to 2030, modelling the effects of current, past and future farm dam impacts by using the CHEAT model (Jordan and Wiesenfeld, 2007). The main disadvantage of TEDI is that it is not spatially explicit. This can have a significant effect on inflows, as catchment areas for individual dams are considered proportional to the size of the dam [this assumption is considered the least defensible component of the TEDI model (Neal et al., 2002)]. Model outputs can be sensitive to the catchment areas defined. The use of a spatially explicit model (CHEAT) has previously improved estimates of the effects of farm dams on the water balance, but the amount of data required to populate a spatially explicit model on a continental scale will likely prove prohibitive. CHEAT has the ability to remove the simplifying assumptions of TEDI (Nathan et al., 2005). A summary of the assumptions removed during each iteration of CHEAT can be found in the work of Nathan et al. (2005). CHEAT has been used to model the effects of farm dams on catchment water balances (Ritson, 2007). As discussed in Appendix D.2, the increase in complexity involved in complex runs of CHEAT as compared with TEDI is likely to prove prohibitive for an Australia-wide water balance calculation.

The input data requirements for TEDI are:

- catchment outflow (or modelled runoff)
- catchment area
- climate information – monthly time series of rainfall and evaporation or monthly means
- land area corresponding to a 5-ML and a 100-ML reservoir
- total volume of farm dams in catchment
- size classes of existing farm dams as a proportion of total
- surface area to volume relationship of farm dams (where Surface area = Coefficient A * [Reservoir volume] $^{\text{Coefficient B}}$)
- a size threshold for stock and domestic dams and irrigation dams (i.e. all dams above a certain size are considered to be used primarily for irrigation; see Appendix D.3.1. for further discussion)
- monthly demand placed upon irrigation dams as a proportion of total annual demands
- demand factors for stock and domestic dams and irrigation dams (proportion of total dam volume to be used in a water year can be greater than 1 if the dam refills during the period of use).
- optional – information regarding dams with bypass flows
- optional – proportion of catchment unaffected by farm dams for iterative natural flow estimation.

Input requirements for CHEAT are all of the above requirements of TEDI, plus the following *Optional* requirements:

- volumes of individual dams
- stream channel and dam network topology
- baseflow and quick flow for each reservoir
- catchment area for each reservoir.

If the Bureau were to develop a new methodology, it may be possible to overcome the shortcomings of TEDI and CHEAT. That is, a methodology could be envisaged that incorporates estimates of farm dam volume over time (from remote sensing or other monitoring devices). However, such a method does not exist as yet. Development of a new methodology to account for the water balance in private storages would require greater Bureau resources than simply adapting pre-existing methods to the Bureau's requirements. Moreover, monitoring changes in storages on the desired temporal scale (monthly or less) may not be possible. Remote sensing is limited by satellite schedules, appropriate atmospheric conditions and processing power. Remotely sensed imagery may, however, prove useful in verifying water balance accounts on a coarser temporal resolution (e.g. seasonally or yearly). Given the risk of not being able to produce a new methodology for farm dam storage estimation in time for the production of the pilot water balance studies, generation of a new methodology was not entertained further.

WIRADA work regarding private storages

WIRADA is currently researching the most appropriate methodology to map farm dams over extensive areas of Australia (Gonzalez et al., 2008). A combination of methods is being considered for large-scale farm dam mapping. The strategy outlined by Gonzalez et al. (2008) is a combination of developing a semiautomatic farm dam mapping technique and creating a strategy to extrapolate the known population of farm dams by using statistical methods. This is being developed because of the likely resources limitation on doing across-the-board farm dam mapping, at least in the short to medium term. The sampling method should provide guidance as to the mapping required to achieve a predefined uncertainty range.

This work will benefit the Bureau's national accounting and assessment of Australia's water resources (as required under Section 120 of the Commonwealth *Water Act* 2007). An increase in accurate farm dam maps will allow for more accurate modelling of the effects of farm dams on the water balance.

Recommendation:

- It is recommended that, for the purposes of producing a water balance, the inflows and outflows of private storages should be modelled to estimate the change in storage, rather than attempting to measure the change in storage of a population of storages.
- The use of a surface area to volume relationship to calculate the volume of water impounded in a reservoir means that it is theoretically possible to estimate the change in storage of an individual reservoir over a period of time via remote sensing. However, it is recommended that this be done on a coarse temporal resolution (e.g. seasonally or greater), as obtaining appropriate imagery is dependent on the satellite schedule and atmospheric conditions (e.g. cloud cover). It is therefore recommended that analysis of remotely sensed imagery be used to periodically verify estimates of water balance elements.

It is also recommended that:

- the pre-existing modelling methodology, TEDI, be used with the best available data to account for the water balance of private storages.
- the WIRADA farm dam mapping project be reviewed on completion and assessed for its applicability to the Bureau's requirements.

3.4.6 Flux terms to Surface water storage

The following flux terms are discussed in the sections of the report relating to the storage from which they originate:

- precipitation (from outside subcatchment) – see section 3.2.1
- inflow from upstream catchment (from outside subcatchment) – see section 3.4.7
- runoff [to rivers, natural surface water features, major and minor storages, private storages, from irrigation] (from Landscape water store) – see section 3.3.7
- interflow (from Landscape water store) – see section 3.3.8
- discharge from groundwater to minor/major storages (from Groundwater store) – see section 3.5.4
- discharge from groundwater to private storages (from Groundwater store) – see section 3.5.4
- discharge from groundwater to natural surface water features (from Groundwater store) – see section 3.5.4
- discharge from groundwater to rivers (from Groundwater store) – see section 3.5.4
- extraction from groundwater to surface water (from Groundwater store) – see section 3.5.7
- urban wastewater/effluent (from Water transport system) – see section 3.6.16
- rural irrigation returns (from Water transport system) – see section 3.6.19
- interbasin transfers of surface water (from Water transport system) – see section 3.6.18
- from marine uptake (e.g. desalination) (from Water transport system) – see section 3.6.17.

3.4.7 Evaporation (exiting subcatchment)

Evapotranspiration from the land surface has already been accounted for in the water balance framework, so the following terms relate directly to evaporation from the Surface water store and rely heavily on the spatial definition of the terms in this store.

Evaporation from major and minor storages

The definition of the spatial extent of major and minor storages as part of the Surface water store will enable evaporation to be estimated by using the methods outlined in Section 3.2.2 for the evaporation from open waterbodies.

Evaporation from private storages

The location and spatial extent of private storages estimated as part for the Surface water store will provide a surface area from which to estimate evaporation using the methods outlined in Section 3.2.2 for evaporation from open waterbodies. It is unlikely that changes in surface are going to be estimated in the water balance calculations, so this term will change only with varying climate conditions. If estimation of private storage by

the aforementioned method is not possible, estimation of evaporation from private storages will be calculated within the TEDI model. The model estimates evaporation of a monthly time-step and takes into account the changes in storages area (pers. comm., Rory Nathan).

Evaporation from natural surface water features

The evaporation from wetlands is dependent on the characteristics of the wetland (in particular, the seasonal fluctuation in the wetland's extent). The magnitude of evaporation loss from wetlands is generally higher than from open water but is dependent on the local environment of the site. Evaporation losses can be higher from wetlands because of the greater surface area of the vegetation, the larger aerodynamic roughness, and the limited stomatal control of the plants (Robinson et al., 1991). The spatial characteristics of the wetlands will be defined as part of the surface water store. In the first instance the evaporation can then be estimated by using the methods recommended in Section 3.2.2 for open-water evaporation. Given the relatively large spatial extent of wetlands, their ephemeral nature, and their combination of open water and wetland vegetation, future estimation of their evaporation should be made directly from high-resolution real-time AET datasets such as those recommended in Section 3.2.2.

Evaporation from rivers

The definition of the spatial extent of rivers as part of the surface water store will enable evaporation to be estimated using the methods outlined in Section 3.2.2 for the evaporation from open waterbodies. Depending on the width of the rivers and the existence of riparian vegetation, rivers can have higher aerodynamic roughness than open water, thereby increasing evaporation. Accurate details on the characteristics of individual river reaches are not available at this stage, so it is recommended that rivers be treated as open waterbodies.

Evaporation from irrigation channels

The accurate estimation of this term is entirely dependent on the spatial definition of the irrigation network and the provision of Water Regulations data to define the periods during which the irrigation channels have water in them. The irrigation network was defined in the MDBSY for the Murray Darling Basin. Satellite imagery was used to estimate the length and width of the irrigation channels, and then depth was assigned on the basis of width classes (McJannet et al., 2008). Given an accurate definition of channel surface area and the period over which the channel is full, evaporation could be estimated by using the methods outlined in Section 3.2.2.

3.4.8 Surface water outflow (flux: exiting catchment)

The surface water outflow is measured directly by data provided through the Water Regulations in rivers where there are downstream stream gauges. For rivers with no downstream stream gauges, the surface outflow could be obtained by river system modelling (some methods are described in Appendix D) or also by using river reach water calculations.

Within river models, typically a conceptual rainfall–runoff model such as SIMHYD is run first to obtain the runoff. The resulting runoff is then routed through a river network using models such as IQQM (used in NSW), REALM (used in VIC) or the River Manager model (being developed by the eWater CRC for national application by regional jurisdictional water agencies). IQQM, REALM and River Manager are briefly described in Appendix D. It is estimated that parameterisation and setting up of river models by the Bureau for the purposes of river streamflow estimation purposes are not possible, given staff and timing constraints. Moreover, construction of such a detailed model, which works on a daily basis, may be in excess of requirements for producing an estimate of river flow for each reach.

Kirby et al. (2008) present an alternative water calculation approach that may be applied to back-calculate river flow at ungauged locations on the basis of river flow mass balance. This method was applied across the Murray Darling Basin as part of MDBSY.

Recommendation:

It is recommended that Water Regulations data be used where available. In cases where streamflow data are not available, it is recommended that the river reach calculation methods of Kirby et al. (2008) be trialled.

3.4.9 Leakage/seepage from Surface water store (flux: to Groundwater store)

Estimation of leakage/seepage from surface water stores from:

- private storages
- major/minor storages
- rivers (including floods) (to Groundwater store)
- natural surface water features (to Groundwater store).

is discussed within Section 3.5.4 as all of these terms are considered jointly in relation to surface water – groundwater interactions.

Recommendation:

It is recommended that leakage/seepage terms be calculated according to the methodology used in Section 3.5.4.

3.4.10 Managed Aquifer Recharge (flux: to Groundwater store)

Data will be provided through the Water Regulations for all forms of 'Managed Aquifer Recharge'. This will include wastewater volumes from the Water transport system that are pumped into aquifer systems and subsequently recovered for irrigation use. Managed aquifer recharge volumes are not currently specified in the Water Regulations but will be included in the next amendments to the Water Regulations.

Recommendation:

It is recommended that data as supplied under a proposed update of the Water Regulations be used.

3.4.11 Bulk urban water (flux: to Water transport system) and the Urban Water Calculator

The following flux terms (detailed in sections 3.4.11 to 3.4.16) refer to the extraction or diversion of water from the Surface water store to the relevant water end-user through the Water transport system. Each term refers to the volume of water directly extracted or removed from the Surface water store, i.e. at the point of extraction, and therefore may not fully correspond to the related water-use terms in the Water transport system table (Section 3.6) which may be used to represent the 'final' water use net of the respective distribution and conveyance loss fluxes. The volumetric difference between extraction (from the Surface water store) and water consumption/use (in the Water transport system) will be accounted for as 'loss' components, described in more detail in Sections 3.4.7, 3.6.14 and 3.6.15.

Bulk urban water extraction is defined for the purposes of the water balance framework as 'the volume of water, measured at the point of extraction or diversion from the Surface water store and distributed into the urban water transport system or transferred to an

internal storage or service reservoir'. The volume of water extracted for bulk urban water use and storage will be provided through the Water Regulations.

Recommendation:

It is recommended that data supplied through Category 7 of the Water Regulations be used (see Appendix A), in conjunction with an understanding of urban water networks and pathways. In a number of cases, urban water data are provided by multiple organisations within a specified reporting unit.

NOTE: The Urban Water Calculator

It is noted that an Urban Water Calculator is currently under development by the Bureau. This Urban Water Calculator, described by Jayatilaka et al. (Urban Water Calculator, *In prep.*) provides a systematic approach to obtaining an untangled, conceptual picture of the complex, integrated water system that represents the urban water transport in water balance regions encompassing major urban centres. The calculator is being developed in consideration of the geographic regions served by water utilities operating within, and in areas adjacent to, the water balance region. The urban water flow pathways resulting from the provision of water supply, wastewater treatment and discharge, and recycled water production are being identified.

The Urban Water Calculator will be used to facilitate the aggregation of Category 7 Water Regulations data by the appropriate reporting unit for water balances and the National Water Account. The calculator will also identify interbasin transfers of bulk urban water where supply networks cross over hydrological boundaries (i.e. disaggregation, where appropriate). The calculator can also identify data gaps where the urban water flow pathways cannot be populated using the Water Regulations data. It is thought that the use of population and/or cadastral information may be used to apportion water used in areas not covered appropriately by the Water Regulations data.

The Urban Water Calculator will not be applied immediately. However, the conceptual urban water pathway diagrams prepared in the process of developing the Calculator will be used as the basis for calculating individual water balance components resulting from the provision of water supply, wastewater treatment and discharge, and recycled water production. See the draft intermediate and detailed conceptual frameworks in Figure 9 and Figure 10, respectively. The differing levels facilitate input of detailed water-use figures, while also allowing aggregation at levels required by the water balance framework.

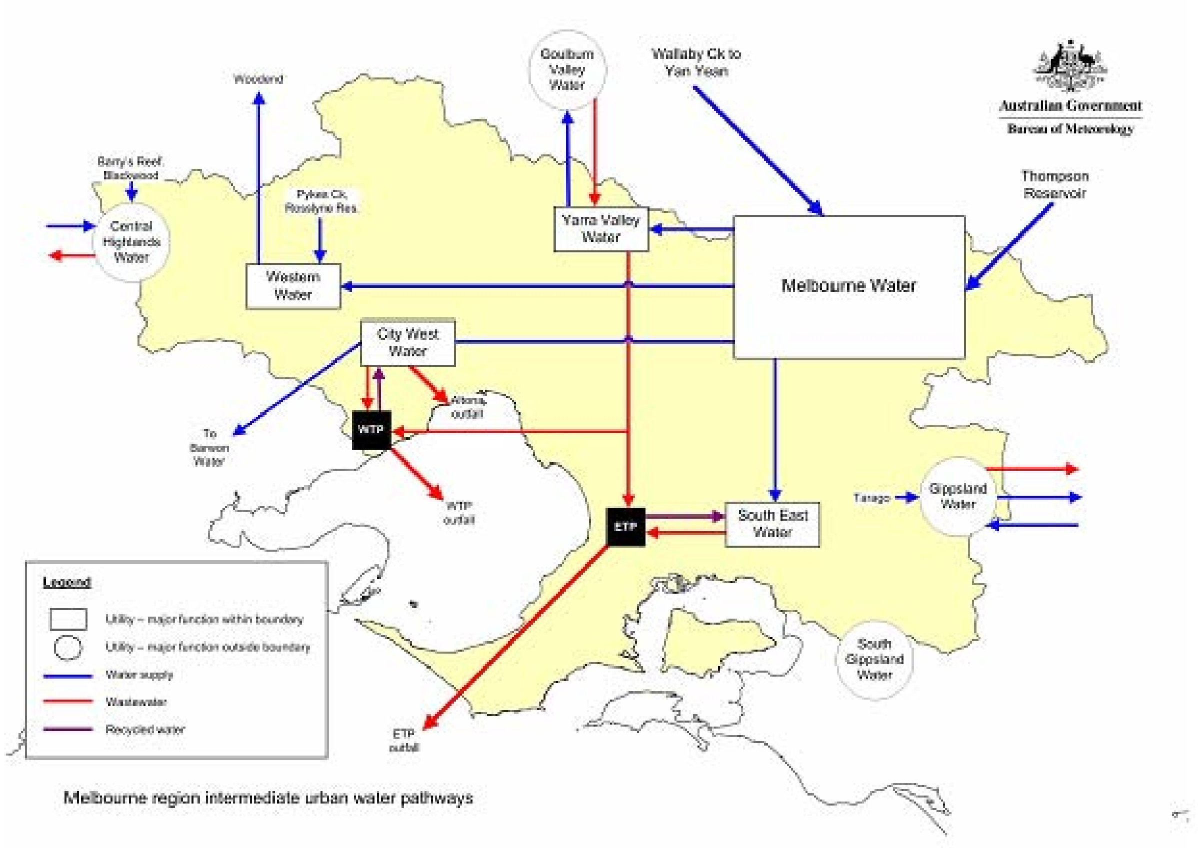

Figure 9. Example of an Urban Water Calculator intermediate urban water pathway diagram

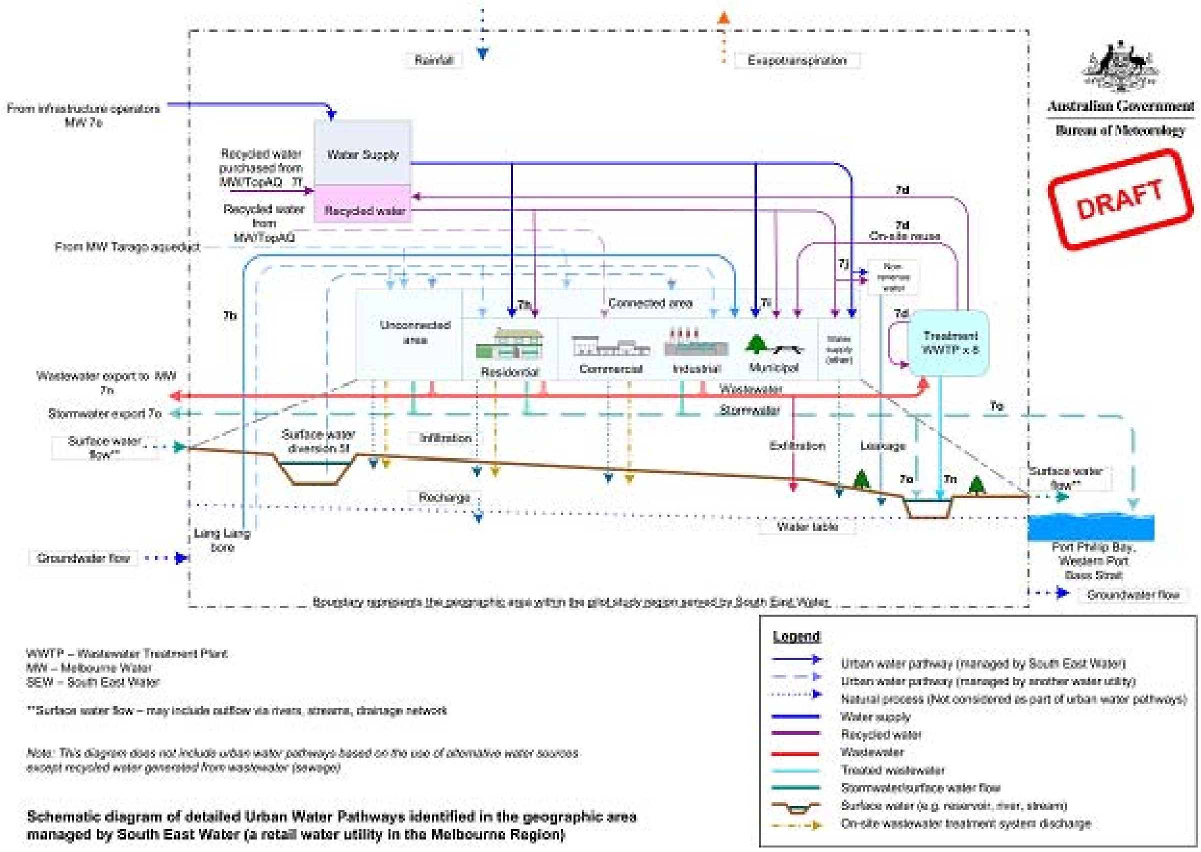

Figure 10. Example of an Urban Water Calculator detailed urban water pathway diagram. This example shows details of the services provided by South East Water, one of the retail water utilities in the Melbourne Region.

3.4.12 Bulk rural irrigation (flux: to Water transport system)

Bulk rural irrigation diversion is defined for the purposes of the water balance framework as; 'the volume of water, measured at the point of extraction or diversion from the Surface water store, directed to an irrigation area or to an off-stream storage for irrigation use at a later date'. The volume of water extracted for bulk rural irrigation use will be assumed to be provided through Water Regulations data.

Recommendation:

It is recommended that data supplied under Category 5a of the Water Regulations be used (see Appendix A). Bulk rural irrigation extraction may also be calculated from Category 5d and 5e data, assuming that any volumes of conveyance and transmission losses (see Sections 3.6.8, 3.6.15 and 3.6.20) between the point of extraction and use can be sufficiently well estimated. If insufficient Water Regulations data are available or the data are of poor quality, then bulk rural irrigation extraction may be derived on the basis of the irrigation water use estimation methods defined in Appendix F. However, these estimation approaches assume that water is diverted for direct irrigation use and do not consider that irrigation water use may also be sourced from offstream storages with a carryover storage volume. These approaches therefore do not give a direct relationship to diversions from the Surface water store. It is not known whether this level of detail will be fully understood for the development of regional water balances.

3.4.13 Private irrigation (flux: to Water transport system)

Private irrigation is defined for the purposes of the water balance framework as 'the volume of water, measured at the point of extraction or diversion from the Surface water store, diverted to a private irrigation area or to a private storage for irrigation at a later date, which is not associated with a bulk irrigation water provider'. The volume of water extracted for private irrigation will be provided through the Water Regulations and will be assumed to be defined as water taken by a self-extractor, which is defined in Schedule 3, Part 1 of the Water Regulations 2008.

Recommendation:

It is recommended that data supplied under Category 5f and 5g of the Water Regulations be used, in conjunction with Category 6e and 6f data where available (see Appendix A). If insufficient Water Regulations data are available or the data are of poor quality, then private irrigation extraction may be derived on the basis of the irrigation water use estimation methods defined in Appendix F. As described above, this assumes direct use of extracted water with no storage. To convert estimated irrigation water use to irrigation extraction it will be necessary to incorporate any assumed or estimated conveyance and transmission losses between the points of extraction and use in order to derive the extraction volume.

3.4.14 Private stock and domestic extraction (flux: to Water transport system)

Private stock and domestic extraction is defined for the purposes of the water balance framework as 'water extracted from the Surface water store to meet private stock and domestic water use requirements'. Estimated private stock and domestic extraction is assumed to be self-extracted water where the user is not directly connected to a reticulated supply system and the water will be used at, or very close to, the point of abstraction. Where stock and domestic water users are connected to a supply system it will be necessary, where possible, to ascertain the proportion of water that may be extracted from private supplies and the proportion provided by a water supply utility. Volumetric water supply to these users may be included within the Category 5 and 7 data provisions, and care will be needed to avoid double-counting of water use and supply.

Transmission and conveyance losses may be assumed to be negligible where water is extracted from a source close to the point of use. The full volume of water extracted for private stock and domestic use is not expected to be provided through the Water Regulations, as this is largely non-metered water use in Australia.

Recommendation:

Private stock and domestic water use will represent a fully estimated water use component of the water balance. This term will incorporate the domestic/residential water use component and the water use requirements for the defined stock or related agricultural practice. The recommended estimation methodologies for each component are described in more detail in Appendix F. Data supplied in accordance with Category 6e and 6g of the Water Regulations may be used in the water-use estimation methods where permits to operate a minor storage or to self-extract from a watercourse can be attributed to stock and domestic water use.

3.4.15 Private commercial/industrial diversions (flux: to Water transport system)

Private commercial and industrial diversions are defined for the purposes of the water balance framework as 'water extracted from the Surface water store for commercial and/or industrial water use purposes, which does not include agricultural water use'. As with private stock and domestic water use, private commercial and industrial water use is assumed to be self-extracted water where the user is not directly connected to a reticulated supply system and the water will be used at, or very close to, the point of abstraction. Where water use by commercial and industrial water users includes reticulated supplies, this volume is assumed to be provided through Category 5 and/or Category 7 Water Regulations data. Therefore, transmission and conveyance losses could be assumed to be negligible. The volume of water extracted for private commercial and industrial use is not expected to be provided through the Water Regulations. The terms 'bulk urban water' and 'bulk rural irrigation' (sections 3.4.11 and 3.4.12) will incorporate the commercial and industrial supply from water utilities and other water providers through Water Regulations data.

Recommendation:

At this stage it is not clear whether private commercial and industrial water use will represent a fully estimated water-use component of the water balance or whether major industrial and commercial water-user information may be included. The recommended estimation methodology is described in more detail in Appendix F. Data supplied under Category 6e and 6g of the Water Regulations may be used in the water-use estimation methods.

3.4.16 Usage from private storage (flux: to Water transport system)

Water usage from farm dams and other private storages will be calculated for each farm dam within the TEDI/CHEAT modelling frameworks. Farm dams are determined as being used primarily for either stock and domestic water supply or irrigation water supply. Stock and domestic dams are usually smaller than irrigation dams; therefore, a threshold volume is user-defined in TEDI/CHEAT. All dams below the threshold are considered stock and domestic and, conversely, all dams above that threshold are considered irrigation. A survey of Victorian landholders determined that 75% of all stock and domestic dams had a capacity of less than 5 ML, whereas 75% of all irrigation dams had a capacity of greater than 6 ML (Lowe et al., 2005); a threshold of 5 ML was chosen for that study. It is recognised that this value may not necessarily reflect the conditions in other areas well. However, in lieu of any further regional estimates, the value will be used as a best estimate for the pilot studies. It is recommended that the Bureau use the 5-ML threshold

when determining private storage use, unless analysis of the data provided under the Water Regulations suggests otherwise. It is recommended that there be an investigation into the adequacy of the widespread application of this threshold following initial use within the pilot studies.

Demand placed on stock and domestic dams is considered to be constant throughout the year in the TEDI/CHEAT modelling frameworks. Victorian survey data indicate that 66% of stock and domestic dams are used equally throughout the year, whereas 26% are used almost exclusively over summer (Lowe and Nathan, 2008). A modified version of TEDI exists in which the user can specify the percentage of stock and domestic dams used equally throughout the year and the percentage used primarily over summer (Lowe and Nathan, 2008). It is recommended that the Bureau attempt to obtain the modified version for comparison with the regular version. Use of this modified method would allow input of monthly varying estimates of private stock and domestic water use, as also required in the water balance framework (section 3.4.14).

Monthly demand placed on irrigation dams within the TEDI/CHEAT frameworks is user-defined as a proportion of total annual demand. It is recommended that the Bureau of Meteorology use data supplied under Category 5 of the Water Regulations as a basis for determining the likely demand patterns placed upon irrigation farm dams.

Demand factors are also considered within the TEDI/CHEAT frameworks. Demand factors are the proportions of a dam's capacity that will be used in a typical water year. A survey of Victorian landholders indicated that the median surveyed demand factor for a stock and domestic farm dam is 0.5, whereas the median demand factor for an irrigation farm dam is 0.84 (Lowe et al., 2005). It is recognised that this value may not necessarily translate well to other regions, but in lieu of any further regional estimates the value will be used as the best estimate for the pilot studies. It is recommended that the Bureau use this figure unless analysis of the data provided under the Water Regulations suggests otherwise.

Recommendation:

It is recommended that:

- the threshold of 5 ML be used to differentiate between smaller stock and domestic dams and larger irrigation dams unless analysis of the data provided under the Water Regulations suggests otherwise
- a copy of the modified version of TEDI be obtained for comparison with the presently released version
- data supplied to the Bureau under the Water Regulations be used as a basis to determine likely demand patterns placed upon irrigation farm dams. The data should be consistent with the private stock and domestic water use estimated as part of the framework (see section 3.4.14).
- the demand factors of 0.5 for stock and domestic farm dams and 0.84 for irrigation farm dams be used, unless analysis of the data provided under the Water Regulations suggests otherwise.

3.4.17 For Interbasin transfer – out (flux: to Water transport system)

Interbasin transfer volume is defined for the purposes of the water balance framework as 'the volume of water exported from the Surface water store of the defined water balance region to an area or location outside the water balance region. The water exports and transfers may include both inter and intra-basin or company transfers depending upon the nature of the water balance domain under consideration'. Where a water utility boundary extends across a catchment boundary this may be considered as an interbasin transfer. Interbasin transfers will initially be moved from the Water transport system of the donor

water balance domain, from where it will be transferred to the relevant store of the respective recipient water balance domain or basin.

Recommendation:

Use data supplied under Category 7 of the Water Regulations (see Appendix A), which will include water extracted for export out of the water balance domain as well as water extracted for use within the domain. Category 7l and 7m of the Water Regulations (see Appendix A) will provide the volume of water exported to other infrastructure operators. Interbasin transfer volumes may also be determined through Categories 3d, 7a, 7d and 7e. It is not clear at this stage whether specific volumes, locations and details of the recipient operator or water balance store can be explicitly identified from Water Regulations data without reliance on sufficient descriptive information and metadata to identify the nature of any water transfers.

The determination of this component may rely substantially on direct consultation with relevant data providers. If consultation is required, it will fall under the Urban Water Calculator project (see Section 3.4.11), currently under development by the Bureau to facilitate the aggregation of Category 7 Water Regulations data by the appropriate reporting unit for water balances and the National Water Accounts. The Calculator will also identify interbasin transfers of bulk urban water where supply networks cross over hydrological boundaries.

3.5 Groundwater storage and fluxes

Aquifers and groundwater systems show a wide range of properties across Australia, and their nature in any area will influence the choice of methods used to estimate groundwater components (i.e. inflows, outflows and storage). A project to provide the Bureau with an interim characterisation of Australian groundwater systems has recently been put to tender, and a more comprehensive analysis is planned for the next 3 years in collaboration with jurisdictional custodians of groundwater data.

At this early stage of the Water Information Program we are already distinguishing between groundwater systems in fractured rock 'upland' areas and alluvial systems in mid and lower catchment areas in pilot areas where these occur. For example, in upland areas in the Murrumbidgee catchment we are evaluating the hypothesis that changes in groundwater storage and groundwater flow out of the upland areas (distinct from local groundwater flows within the areas that contribute to river baseflow) are not significant in calculations of annual catchment water balance. Furthermore, the total groundwater extraction for human use is not considered significant to the catchment water balance in these upland areas. Thus a simple representation of the water balance of the upland groundwater systems is likely to be appropriate for a Water Resource Assessment at the scale of the whole Murrumbidgee catchment.

A range of methods for estimating components of groundwater balance will be required to represent the range in types of groundwater systems. The intention is to develop different approaches to estimating groundwater balance in a limited number of different types of groundwater systems. Furthermore, groundwater flow processes are often slower than other water fluxes in a catchment and are often better represented on time scales of 10 years or longer; this may require particular attention in the presentation and use of groundwater balances.

Numerical groundwater models

Numerical groundwater models provide an approach to quantification of all major groundwater fluxes and the change in groundwater storage. Models are constructed and initialised to represent one or more aquifer systems using available information about the nature of the extent, depth and hydraulic properties of the geological layers across a study area. Details of groundwater recharge, groundwater extraction in pumping bores,

interaction with rivers and other water balance components can also be entered into the model. Most groundwater models require specification of model boundary conditions that control groundwater flow across boundaries. Information about conditions can be sparse at the boundaries; moreover, there are a limited number of algorithms available to represent boundary flows, and changes in conditions over time are often difficult to represent. The models are usually calibrated against groundwater level measurements at a limited number of calibration bores.

The brief description above provides context to some of the advantages and disadvantages of using numerical groundwater models in estimating groundwater balance components.

Advantages:

- Mass is conserved: water that enters a groundwater model will be accounted for by an equivalent outflow volume and change in storage of the groundwater system.
- The interaction of different groundwater flow processes is accounted for in a model.
- The concept of the groundwater system is more fully implemented in a numerical model, and such a model arguably would influence the system response to environmental conditions more than it would if groundwater flow components were evaluated separately.
- Over time a model can be updated and refined and the representation of the real groundwater system should be improved. A model provides a vehicle for accumulating knowledge of the groundwater system components and their interaction as an integrated system.

Disadvantages:

- The simple representation of the nature of groundwater systems may misrepresent the complexities that are likely to occur in the natural groundwater system, e.g. often a low density of input data points can result in misrepresentative interpolation or extrapolation of aquifer properties.
- The simple representation of natural flow processes may also misrepresent the complexities of fluxes such as groundwater recharge, model boundary conditions for flow, and interaction with rivers.
- There will be a range of possible realisations of model parameters that will meet the same criteria for calibration of a groundwater model but are likely to provide different results for components of groundwater balance (non-unique calibration).
- Substantial amounts of resources are required to develop and calibrate each groundwater model to best practice standards.

Groundwater models are most often used in scenario testing. For example, a model might be used to provide an indication of the effects of groundwater extraction on groundwater levels across an aquifer after 10 or 20 years of extraction at different annual rates. In this context the value of a good groundwater model is clear. However, the value of a groundwater model is less clear in the context of an annual water resource assessment, for which the Bureau will have data for groundwater levels observed throughout the period of assessment; observed changes in groundwater level are arguably more indicative of the groundwater resource condition than outputs from a groundwater model would be, especially on an annual time frame.

At this early stage of the implementation of water resource assessments we are not proposing to use groundwater models in our assessments. Options are being considered for future collaboration with the jurisdictional agencies responsible for groundwater management on the use and application of groundwater models in areas with substantial groundwater resources.

The approach to estimating an annual water balance of a catchment or reporting entity with four water stores was introduced in Section 2. This section refers to a 'Groundwater store' among the other stores. However, we recognise that methods for estimation of groundwater storage and groundwater fluxes must evaluate groundwater resources aquifer by aquifer before accumulating the terms relating to each aquifer system present to represent the groundwater store as a whole. Further details of the conceptual model of groundwater resources and their estimation will be provided elsewhere.

3.5.1 Groundwater storage

The Groundwater store in an aquifer system is categorised by evaluating whether or not the groundwater is renewable and whether it is saline or fresh, as defined further below. This categorisation is necessary to avoid misrepresenting the nature of the availability of the groundwater resource. A low-salinity and sustainable (or renewable) resource is only a part of the total volume in groundwater storage. Some aquifer systems may include more than one category of groundwater.

Renewability of groundwater storage

The recognition that some groundwater resources are renewable whereas others are non-renewable has implications for groundwater management and the way in which the volume of water in the groundwater store can be interpreted. It is important to understand that the use of non-renewable groundwater represents permanent depletion of the groundwater store under existing climatic conditions. Use of this water is often referred to as 'groundwater mining', because the resource will not be replaced by natural groundwater recharge processes (as far as is known).

In the AWR 2005, non-renewable groundwater was defined as 'groundwater extracted from an aquifer that receives limited or no recharge', whereas renewable groundwater was defined as 'groundwater extracted from an aquifer that receives recharge from rivers, rainfall, or from other aquifers'.

According to Margat et al. (2006), the renewability of groundwater resources is controlled by two main factors:

- hydrogeological structure (the presence of confining beds and flow barriers prevents recharge to the aquifer)
- climatic conditions (low rainfall and runoff in arid and semi-arid areas result in very low and episodic recharge).

The climatic conditions are relatively easy to assess on the basis of:

- average annual rainfall ≤300 mm/year (a commonly used threshold under which recharge is assumed negligible)
- climate classification schemes (e.g. the Koeppen classification)
- rainfall variability index (useful for determining where episodic recharge occurs)
- modelled groundwater recharge or deep drainage (e.g. AWAP or WAVES deep drainage).

However, it is important to recognise that aquifers can also be recharged by processes other than rainfall recharge – such as river seepage, flooding, irrigation and inter-aquifer exchange – that may not be revealed by climate datasets.

It is more difficult to assess the hydrogeological structure of aquifers. One of the important considerations is aquifer type (confined, unconfined or leaky confined), data on which are not currently available for the Australian continent. These data may become available in late 2009 through a consultant project providing Interim Spatial Groundwater data for the spatial information database being set up for use within the Bureau.

Other, more detailed ,analyses can also be used to assess the renewability of groundwater:

- groundwater dating (e.g. using carbon-14 and helium-3)
- recharge analyses (e.g. of chloride, oxygen-18 and deuterium)
- groundwater flow models.

These analyses are more useful for local or regional-scale studies rather than a national water assessment.

Recommendation:

It is recommended that renewability be assessed on an aquifer by aquifer basis after considering average annual rainfall, rainfall variability, hydrogeology, recharge mechanisms, streamflow, irrigation and any detailed studies of the aquifer, such as groundwater dating.

Salinity of stored groundwater

The classification of the Groundwater store as saline and non-saline recognises that salinity is an important control on the use of groundwater. Non-saline groundwater is traditionally considered a resource, whereas use of saline groundwater is limited, although this is changing, with desalination of saline groundwater becoming more common at mines and in towns such as Dalby in Queensland. Additionally, a change in the proportion of saline to non-saline groundwater may be a useful indicator of deterioration of groundwater conditions and the potential onset of salinity problems.

In AWR 2005, saline groundwater was defined as having a salinity (expressed as Total Dissolved Solids or TDS) equal to or exceeding 3500 mg/L and non-saline (or fresh) groundwater as having a salinity less than 3500 mg/L. A salinity of 3500 mg/L is a typical upper limit for irrigation, although the threshold does vary. Groundwater that is more saline can still be used for stock watering, recreation and industry(Table 7).

Table 7. Beneficial use of groundwater-based TDS (mg/L) (Victorian Environment Protection Authority, 1997)

Beneficial use	TDS (mg/L)
Potable water supply – desirable	0 to 500
Potable water supply – acceptable	500 to 1000
Potable mineral water supply	0 to 3500
Irrigation	0 to 3500
Stock watering	0 to 13,000
Primary contact recreation	0 to 13,000
Industrial water use	No limit
Buildings and structures	No limit
Maintenance of ecosystems	No limit

The salinity of groundwater is usually measured as electrical conductivity (EC; in µS/cm), which can be converted to TDS in mg/L. The approximate relationship between EC and TDS is TDS (mg/L) = EC (µS/cm)/0.67 (ANZECC/ARMCANZ, 2000). Consequently, the salinity threshold of 3500 mg/L corresponds to an EC of 5224 µS/cm.

Information that can be used to determine the salinity of groundwater in an aquifer includes:

- EC measurements from the Water Regulations 2008
- existing groundwater salinity mapping
- groundwater beneficial use mapping
- Airborne Electro-Magnetics (AEM)–derived salinity mapping.

Recommendation:

It is recommended that groundwater with salinity <3500 mg/L is considered to be non-saline and groundwater with salinity ≥3500 mg/L should be considered saline. Groundwater salinity should be assessed by using existing hydrogeological mapping where available, as well as measurements of groundwater EC collected in response to the Water Regulations 2008.

Estimating the stored groundwater volume

Groundwater storage is the state variable of the 'Groundwater store' (Table 1). Change in groundwater storage is expected to be equal to the difference between the sum of all groundwater inflows and the sum of all groundwater outflows (Table 4)

The term 'groundwater storage' is used to describe both the total volume of groundwater within an aquifer, including water retention (known as total storage) and the volume of groundwater that can be removed by pumping (referred to as extractable storage). 'Extractable storage' is the term commonly used in studies estimating the available groundwater resource. In contrast, total groundwater storage is analogous to the surface water storage terms in the Bureau's water balance framework, which include dead storage (Barratt, 2008). It is important to recognise that neither of these terms represents the volume of groundwater that can be extracted from an aquifer in a given year; this volume is strongly dependent on the nature of the aquifer and the number and location of groundwater extraction bores.

Other approaches consider groundwater storage relative to an arbitrary level or in reference to a particular management regime. For example, in AWR 2005, groundwater storage for NSW was assessed relative to a depth of 20 m. In this case, it is the change in storage rather than the volume that is important. One of the benefits of this approach is that only the depth to groundwater is needed (rather than the groundwater elevation), and hence bores without a surveyed reference elevation can be used.

A change in groundwater storage will need to be considered in the context of the magnitude of the volume of extractable groundwater.

Data inputs required are:

- aquifer boundaries
- aquifer geometry (thickness and elevation of top and base of aquifer)
- aquifer properties (porosity, specific yield and storage coefficient)
- elevation of watertable or potentiometric surface
- streamflow measurements (for evaluation of groundwater baseflow only).

Note that, of the inputs listed above, data provided through the Water Regulations 2008 will cover only point measurements of groundwater level (from groundwater observation bores) and streamflow data at gauge locations. Some information about aquifer properties may be provided through the metadata that are intended to provide context to the use of groundwater levels, but providion of this data is not currently assured by the Water Regulations. A collation of published aquifer properties are also expected to be provided by the interim characterisation of Australian groundwater systems (external contract in progress).

Models/methods for estimating changes in groundwater storage

1. Volumetric calculations

A change in stored groundwater volume over a fixed period is calculated by first estimating the spatially averaged change in volume of the saturated aquifer in an unconfined system, or estimating the change in groundwater potential of a confined aquifer system. These calculations are likely to require interpolation and extrapolation from point measurements of groundwater level; some interpolation methods are reviewed in Appendix G. Groundwater storage (total, extractable or relative change) can then be estimated by using simple volumetric calculations based on aquifer area, saturated thickness and aquifer properties. Where spatial data are available, the calculations can be performed and automated by using a GIS.

As discussed above, there are three possible representations of groundwater storage:

1a. total storage

1b. extractable storage

1c. Change in storage relative to a reference level.

2. Analysis of river baseflow

In some regions the groundwater storage capacity is small and the movement of water as groundwater flow down-catchment (or out of the surface water drainage catchment) is largely insignificant. The upland areas of the Murrumbidgee are examples of this type of region, and in these areas a primary groundwater component of the catchment water balance is groundwater discharge to rivers from the 'Groundwater store'.

Groundwater discharge to a river can be estimated by using an analysis of streamflow to extract the stream 'baseflow', which can be considered to be groundwater discharge. A change in baseflow over time can be used to indicate a change in groundwater storage. However, it is important to consider that, because of groundwater extraction, river bank storage and evapotranspiration of groundwater, baseflow discharge is not necessarily directly equated to a change in groundwater storage (Scanlon et al., 2002).

There are a number of techniques, including numerical filter techniques, for extracting baseflow (see Lyne and Hollick, 1979; Nathan and McMahon, 1992). The work of Brutsaert (2008) and earlier preceding works provide a methodology to estimate groundwater storage from baseflow; this methodology is currently being investigated. Other methods for estimating baseflow and making inferences about groundwater storage may be evaluated in future if these methods are thought to offer advantages to estimation of catchment water balance.

3. Groundwater model – MODFLOW

Groundwater models directly offer an estimate of changes in groundwater storage as part of the groundwater mass balance. As discussed in the groundwater introduction, we will not use groundwater models in the initial pilot water balance investigations, although models may offer useful approaches for some areas in future work.

Recommendation:

It is recommended that methods 1c (volumetric change) and 2 listed above be trialled in the pilot studies.

It is suggested that the final step in estimating changes in groundwater storage is to evaluate whether the changes have occurred in 'fresh' or 'saline' aquifers and also to assess groundwater renewability. This approach is considered appropriate because the spatial distribution of groundwater salinity does not change significantly on an annual basis in many areas and the data for groundwater salinity are often limited. It is noted that such disaggregation will not be undertaken in the initial pilot studies.

Methods for estimation of groundwater storage and fluxes are being developed as part of the WIRADA WRAA project (Crosbie et al., 2008). Although these methods were not available at the time of writing, it is considered that the methods developed within the project will be used in subsequent years.

3.5.2 Regional groundwater flow (flux: to/from adjoining Groundwater stores)

Groundwater flow can be considered to be regional when it occurs over distances exceeding 50 km and is at the scale of river basins (Coram et al., 2000). For the purposes of the Bureau's water balance framework, the term regional groundwater flow is used to describe the movement of groundwater into and out of an area of interest, such as an aquifer or sub-catchment, including flow within both the shallow and deeper aquifers.

Data inputs required are:

- groundwater levels
- hydraulic conductivity
- saturated thickness
- aquifer area.

Models/methods for estimating regional groundwater flow

1. Simple GIS calculations

Groundwater flow can be estimated according to Darcy's Law by using spatial data as inputs. This method uses a groundwater level surface and an assessment of the gradient of this surface at the boundary of the area of interest. A comparison of interpolation methods to generate a groundwater potential surface from point measurements of groundwater level is provided in Appendix G. An interpolated groundwater potential surface is also used in the assessment of groundwater storage.

2. Groundwater model

Regional groundwater flow can be modelled by using MODFLOW, a three-dimensional groundwater flow model. The Zone Budget module can be used to derive subregional water budgets.

Recommendation:

It is recommended that regional groundwater flow be estimated by either the GIS-based approach or from groundwater models in the pilot investigations. Where possible a comparison of these methods should also be made.

3.5.3 Diffuse groundwater recharge (flux: from Landscape water store and Surface water store)

Diffuse groundwater recharge here refers to the fraction of rainfall or irrigation that recharges groundwater; it is fairly uniform over large areas. Diffuse recharge is labelled 'recharge' in Table 2, and in simple terms it is the water flux that drains below the vegetation root zone and then passes into the saturated zone of the groundwater system. Localised recharge here refers to concentrated recharge, such as from rivers, lakes and floods (Scanlon et al., 2002); it occurs only in a fraction of the landscape. These components of localised groundwater recharge are labelled 'seepage' in Table 3 and Table 5 and are discussed further in Section 3.5.4. Diffuse groundwater recharge is usually the main input to the groundwater store in high rainfall areas, whereas in arid to semi-arid areas recharge is often episodic and/or localised.

The processes of diffuse or localised groundwater recharge can usually occur both as a flux to a groundwater resource volume and a flux out of a groundwater resource volume. For example, diffuse groundwater recharge is typically counterbalanced by capillary rise of groundwater (Section 3.5.5), and localised recharge (seepage) is counterbalanced by groundwater discharge (often seepage/discharge processes are referenced as groundwater – surface water interaction, Section 3.5.4).

Considering the definition of recharge further, many terms (such as drainage, net infiltration or percolation) are used in the literature to describe water movement below the root zone, and these fluxes are often equated to groundwater recharge. However, in the assessment of water resources we propose to differentiate between water draining below a root zone that may or may not reach the watertable (*potential* recharge) and water that has become part of a more connected groundwater resource below the watertable (*actual* recharge) (Rushton, 1997; Petheram et al., 2000). Changes in the groundwater resource volume are evaluated from changes in groundwater levels (for unconfined aquifers these levels are taken to represent the watertable surface). Thus, if it is possible to differentiate between actual and potential recharge, an estimate of actual recharge is preferred to an estimate of potential recharge.

Furthermore, episodic groundwater recharge and recharge of unconfined groundwater systems with deep watertables (e.g. ≥30 m below the surface) are likely to be best considered on time scales of decades or longer. Representation of recharge in arid and semi-arid zones will need to be considered further in later work.

Two recharge processes that are not yet addressed in this review are:

- recharge from flood events (use of remotely sensed estimates of areas and duration of flooding may be feasible)
- recharge in urban environments (factors to consider would include area of impervious surface and volumes of water that may be directed to 'recharge pits' for enhanced recharge).

Many reviews are available on physical and chemical techniques of estimating groundwater recharge (Scanlon et al., 2002; Walker et al., 2002). However, this remains one of the most difficult catchment water fluxes to estimate accurately over large areas; for further discussion see Appendix G. Recharge of a confined aquifer is briefly discussed below, followed by a general discussion of estimation of diffuse recharge. Problems associated with estimating seepage to groundwater from private reservoirs are discussed further in Appendix D.3.1.

Recharge of a confined aquifer

Recharge of a confined aquifer can occur through leakage from the confining layer and also through 'unconfined aquifer recharge processes' (e.g. river and rainfall recharge) in areas where the confined aquifer outcrops (or subcrops beneath an unconfined and hydraulically conductive layer). Also, preferential infiltration of runoff may occur at the boundaries between locally outcropping bedrock and the up-gradient edge of a confined aquifer system. Leakage from an unconfined groundwater system to a confined groundwater system represents a flow that is internal to the Groundwater store (described in Section 2.2) and as such would not need to be quantified. Nevertheless, this type of flow is relevant to the management of groundwater resources in some areas (e.g. Gnangara Mound, WA).

In all cases, groundwater recharge to a confined aquifer is particularly difficult to estimate. Geochemical methods (e.g. ^{14}C velocities and Cl mass balance) can accurately estimate recharge and leakage to confined aquifers (see Appendix G). However, geochemical data are often local and unable to be used to assess recharge on an Australia-wide scale. Another method is to estimate groundwater throughflow at the top of the groundwater flow path in the confined aquifer; alternatively, in the case of areas

where acceptable groundwater models exist, these models may provide a reasonable estimate of confined aquifer recharge.

This type of flow process is not described further here.

Data inputs required for estimating diffuse groundwater recharge include:

- climatic conditions (rain, ET potential)
- soil hydraulic properties
- nature of the land surface (especially in urban environments; what is the fractional area of the impervious surface?)
- vegetation type description (canopy density, root depth)
- depth to watertable
- irrigation water applied
- underlying geology.

Models/methods for estimating diffuse groundwater recharge

These methods are described in greater detail in Appendix G.

1. WAVES model

WAVES is a one-dimensional daily climate–soil–vegetation model that considers plant physiology, water use and soil physics to model water movement and soil water content in the unsaturated zone. This model estimates potential diffuse recharge to groundwater.

2. AWAP model

The AWAP project used a fully dynamic water balance model called 'WaterDyn', which calculates drainage out of the soil profile as a product of soil hydraulic conductivity and moisture content. This model estimates potential diffuse recharge to groundwater.

In arid to semiarid climates, as in large parts of Australia, evaluating recharge from water balance models and remote sensing is not always straightforward. For example, the small recharge amount calculated from the difference between rainfall and actual evapotranspiration (E_a) is normally less than the accuracy range of E_a determination (de Vries and Simmers, 2002). In addition, in these areas recharge to groundwater can be episodic and localised. Hence it becomes important to review these recharge rates by using different methodologies.

3. Watertable Fluctuation (WTF) Method

A time series of watertable levels showing fluctuations in response to groundwater recharge events can provide estimates of local recharge over a few days to a few years. This method assumes that either a seasonal variation or an event-based variation in groundwater recharge rates occurs; the watertable rises in response to periods of high groundwater recharge and then falls following these events. Assumptions of the method include 1) no significant lateral groundwater flow occurring during the period of high groundwater recharge and 2) strong dependence on the estimate of aquifer-specific yield (see Appendix G).

Estimation of annual actual recharge across a catchment is likely to be difficult with this method, although it may provide a useful check on other methods in some areas. This method can be used also to assess localised recharge due to floods or stream leakage and therefore to measure surface water – groundwater interaction.

4. Groundwater geochemistry

Levels of tritium (^3H) and CFCs in groundwater may reflect average recharge rates over years to decades, whereas Cl and ^{14}C levels may reveal average recharge on longer time scales (Cook and Bohlke, 2000; Scanlon et al., 2002; Cartwright et al., 2007).

These estimates may provide checks on long-term average actual recharge in some areas but are unlikely to be useful as part of an annual catchment water balance.

5. Percentage of rainfall or irrigation

In data-poor areas, groundwater recharge is often estimated as a percentage of local annual rainfall or irrigation depth applied. This approach is typical in groundwater modelling studies where recharge estimates can be further refined during calibration.

Reviews of groundwater recharge in Australia indicate that recharge is usually less than 2% of rainfall in arid to semi-arid areas (Tolmie and Silburn, 2004; Cartwright and Weaver, 2005), whereas in high rainfall areas, such as in north Queensland, recharge can vary up to 33% of rainfall (Petheram et al., 2000). In addition, Petheram et al. (2000) showed that soil type and vegetation type are important factors in constraining recharge rates; they found no recharge under trees in medium to high rainfall zones (i.e. <600 mm/year) and a recharge rate of 30% of rainfall on sandy soils with a rainfall threshold of 250 mm.

Diffuse groundwater recharge resulting from irrigation is often estimated as approximately 10% of irrigation depth, depending on the soil type and crop, in part reflecting the need for a leaching fraction to drain salts that are carried in irrigation water to depths below the crop root zone.

In the MDBSY project, recharge values for the groundwater models of the lower Murrumbidgee alluvium were estimated to be 0.9% of annual rainfall and 9.6% of irrigation (CSIRO, 2008b). This methodology has the disadvantage of not considering local variation in recharge due to localised recharge and episodic recharge due to floods or short and intense rainfall events.

Recommendation:

It is recommended that Method 1 (WAVES model output) and Method 5 be used in the pilot water balance investigations. Where possible a comparison with alternative methods (AWAP, WTF) should also be made.

3.5.4 Groundwater – surface water interaction (flux: to/from Landscape water store and Surface water store)

The interaction between groundwater and surface water takes place in two ways: namely, streams gain water from groundwater through the streambed when the elevation of the watertable adjacent to the streambed is greater than the water level in the stream, and streams lose water to groundwater by outflow through the streambed when the elevation of the watertable is lower than the water level in the stream. Within any particular stream, it is not uncommon to have different reaches gaining or losing water, or the same reach losing or gaining water at different times of the year.

The processes relevant to surface water – groundwater (SW-GW) interaction can be categorised as being groundwater driven, surface water driven, or driven by both (groundwater – surface water driven) (Rassam and Werner, 2008). Stream depletion, a groundwater-driven process, is defined as the reduction of streamflow due to induced infiltration of stream water into the aquifer or the capture of aquifer discharge to the stream (Theis, 1941; Sophocleous, 1997). In a situation where a stream is connected to the aquifer via a fully saturated material, pumping of groundwater can lead to stream depletion. Surface water–driven processes include overland flow and throughflow, river flow attenuation, instream storages and reservoir operation, off-stream storages, bank storage, and over-bank flooding. The important SW-GW driven processes are SW-GW interaction in wetlands and evaporation.

Within the water balance tables (Table 3 and Table 4), fluxes that may require a SW-GW model include interaction between rivers and groundwater, storages and groundwater,

and natural surface water features and groundwater. Interaction implies that either seepage (i.e. localised groundwater recharge) or groundwater discharge can be occurring at adjacent locations or even at the same location but at different times under different environmental conditions. Estimates of seepage from irrigation channels and urban water transport systems are also considered in this section. Some methods used to estimate diffuse groundwater recharge may also be useful for estimating seepage (e.g. the watertable fluctuation method).

Some of the potential methods are being investigated in the WIRADA Water Analysis and Accounting project and in other CSIRO/eWater projects.

Data inputs required include:

- riverbed hydraulic properties
- water levels in rivers
- groundwater levels alongside rivers
- catchment daily rainfall
- alluvial aquifer storage capacity
- digital elevation model (DEM).

Models/methods for estimating groundwater – surface water interaction

Some of these methods are described in greater detail in Appendix G.

1. Channel Water Balance

A channel or river water balance can be calculated where inflows to, and outflows from, an irrigation channel or a length of river are known. This may provide a useful check on other methods. The CSIRO models described below attempt to provide a little more context to groundwater – surface water interaction. It may be possible to develop a modelling approach to investigate 'channel water balance' for selected river reaches.

2. CSIRO Upland model

Groundwater surface water interaction in upland catchments is being included in the eWater/NWC catchment water and solute generation model WaterCAST. This model is an adaptation of the 2CSalt model that allows for time lags in water movement to a catchment outlet.

3. CSIRO Link model

This is an interaction model that is currently being developed by eWater CRC/NWC to represent these processes in the RiverManager model for regulated rivers; it is briefly described by Rassam and Werner (2008).

4. CSIRO Floodplain Processes model

The floodplain processes model represents an increase in the complexity described by the link model. The model is also currently being developed by eWater CRC/NWC to represent interaction processes in RiverManager model for regulated rivers. It is briefly described by Rassam and Werner (2008) and represents interaction of rivers, floodplains and groundwater in areas such as those found in the Murray River trench in South Australia.

5. MDBSY Connectivity model

SW-GW connectivity mapping is used to estimate the direction and magnitude of groundwater flux to or from streams and rivers. The approach uses Darcy's Law, and hence estimates of hydraulic conductivity and groundwater gradients need to be available. River and groundwater levels are compared at a single point in time to provide a snapshot of the direction and magnitude of the flow between surface water and

groundwater. The approach was developed as part of the Murray-Darling Basin Sustainable Yields (MDBSY) Project.

The model provides:

- an alternative approach to numerical models, allowing surface water modelling and groundwater modelling estimates to be checked
- an initial indication of groundwater surface water interaction that can be used as the basis for more detailed conceptualisation as part of modelling
- a powerful visual aid.

6. Q-Lag model

This method involves comparing daily streamflow percentiles derived from the gauging station record with daily rainfall from a representative climate station within the catchment. By taking a frequency analysis approach, the streamflow and rainfall data are compared at different percentiles. Three case studies have been examined, namely; Wilsons River, NSW (a gaining stream); Ovens River, Victoria (a dominantly gaining river); and Mooki River, NSW (a losing stream) (Brodie et al., 2007).

Q-Lag analysis has the potential to derive additional information about stream–aquifer connectivity that remains hidden from more conventional hydrographic analysis.

7. IHACRES_GW

The three-parameter algorithm IHACRES was introduced by Jakeman and Hornberger (1993) and was developed by distinguishing the components of rainfall that become 'quick' and 'slow' runoff (quick runoff is surface runoff, whereas slow runoff is the sum of rapid subsurface runoff, delayed subsurface runoff and groundwater discharge). The model identifies a unit hydrograph for total streamflow from continuous time series of rainfall and streamflow.

IHACRES_GW, developed by Ivkovic (2006), includes the influence of groundwater exchanges in a spatially lumped rainfall–runoff model (IHACRES), combined with a simple groundwater bucket model that maintains a continuous water balance account of groundwater storage volumes for the upstream catchment area relative to the base of the stream, assumed to be the stream gauging station. Recently this model has been coupled with the catchment moisture deficit (CMD) version of the IHACRES non-linear module (Croke and Jakeman, 2004), so that the influence of climate change and variability on the impacts of groundwater extraction on streamflow can be simulated. Further improvements are being tested (Herron and Croke, In Press).

Baseflow separation techniques that use algorithms have the advantage that they can be translated into computer codes easily and have a consistent approach when working with long, continuous records of streamflow data. Conversely, a spatially lumped modelling approach in the management of water resources has a number of limitations, including those arising from the lack of spatial considerations; also, the choice of values when attempting a baseflow separation is very subjective and expert judgement is required.

Recommendation:

It is recommended that the MDBSY Connectivity model be applied to the pilot catchment regions.

3.5.5 Groundwater ET / capillary rise

As stated earlier, diffuse groundwater recharge is typically counterbalanced by capillary rise of groundwater (or groundwater ET) and localised recharge (seepage) is counterbalanced by groundwater discharge. (Often these processes are referenced as groundwater – surface water interaction, Section 3.5.4.) Where possible, an estimate of diffuse groundwater recharge should estimate 'net diffuse groundwater recharge' (the net water flux downward across the watertable over a 12-month period). In areas with shallow watertables, the net recharge may be negative (i.e. there may be a net upward movement of groundwater across the watertable to the unsaturated soil zone or atmosphere).

In areas with shallow watertables, tree roots may penetrate below the watertable and take up groundwater, which will then be transpired by the tree canopy: this would contribute to groundwater evapotranspiration. In terms of catchment water balance, groundwater ET is effectively the same as capillary rise of groundwater from beneath the watertable up to the unsaturated soil zone. Satellite estimates of actual evapotranspiration (Section 3.2.2) would be expected to include groundwater ET as a component of actual ET. Capillary rise may often result in ET also – perhaps over a longer time period than root uptake of groundwater.

It would be difficult to estimate groundwater ET and capillary rise over large areas, but these factors are expected to be significant only in shallow watertable areas (where depth to watertable is <8 m).

Recommendation:

It is recommended that calculation of groundwater ET and capillary rise not be attempted at this stage, because these factors are likely to be significant only in small areas of the catchment. Note that estimates of actual ET and net groundwater recharge may implicitly account for part or all of this flux.

3.5.6 Groundwater–marine interaction

In coastal locations, the fresh groundwater beneath land discharges near the coast and mixes with saline groundwater beneath the sea floor. Salt water is also found adjacent to fresh water in inland areas, often in the same aquifer, but we focus here on the interface between fresh groundwater and salty marine groundwater.

Fresh groundwater is less dense than seawater, and therefore the fresh/salty water interface is not vertical and salty water can seep into the lower part of an aquifer that outcrops in the ocean beneath sea level. Fresh groundwater usually grades into saline water with a steady increase in the salinity of the water. In some situations, the contact may be quite sharp, with a very thin zone of mixed water. The mixture of fresh water and salt water results in a zone in which there is a salinity gradient. If the aquifer is subject to hydraulic head fluctuations caused by tides, the zone of mixed water will be enlarged.

The interaction of saline marine water and fresher groundwater underlying land areas is less important where the direction of groundwater flow is clearly towards the marine environment. In this case a gradient in groundwater levels on the landward side toward the coast will allow a groundwater flux to be estimated (as for regional groundwater flow above).

Data inputs required are:

- groundwater levels along the coast
- digital elevation model (DEM)
- conceptual model of hydrogeology.

Models/methods for estimating groundwater – marine water interaction

1. Simple GIS calculations

Simple GIS calculations can be used to estimate groundwater flow at the coast. This method follows the description provided in Section 3.5.2 and requires that a hydraulic gradient in groundwater levels be estimated in an aquifer near the coast. This method will be most appropriate where groundwater flow is clearly from the land to the marine environment.

2. Ghyben-Herzberg

Fresh water is lighter than salt water. Fresh water has a density of 1.0 g/cm^3, whereas salt water is slightly denser at 1.025 g/cm^3. Therefore, fresh water floats on top of salt water. The weight of the rain water that percolates into the groundwater depresses the salt water beneath it, forming a profile that has the appearance of a lens. This is called the Ghyben-Herzberg lens. For a given aquifer environment the width of the zone in which seawater underlies fresher groundwater can be used to calculate a freshwater discharge rate (refer to Appendix G for more details).

3. SEAWAT

SEAWAT is a groundwater modelling package that simulates variable-density, transient, groundwater flow in three dimensions. The advantage of using SEAWAT for variable-density modelling over other, similar, programs [SUTRA (Voss, 1984), HST3D (Kipp, 1997) and MOCDENSE (Sanford and Konikow, 1985)] is that it is coupled to two popular software packages, namely MODFLOW and MT3DMS. It uses the finite difference solution method.

The development of SEAWAT code is based on the assumptions that Darcy's law is valid (laminar flow), the standard expression for specific storage in a confined aquifer is applicable, the diffusive approach to dispersive transport based on Fick's law can be applied, and isothermal conditions prevail. The porous medium is assumed to be fully saturated with water. A single, fully miscible liquid phase of very small compressibility also is assumed. SEAWAT is based on the concept of equivalent freshwater head in a saline groundwater environment.

Groundwater models are typically applied to single catchments and may not be suited to regional analysis. Coastal environments are difficult to characterise with a model, because groundwater inflows might be coming from a large upland area.

4. FEFLOW

FEFLOW is a 3D finite-element groundwater modelling package that can process problems involving complicated geology, unsaturated flow, density-dependent flow (saltwater intrusion), or thermal convection, where traditional modelling programs have proven to be unsuitable.

Groundwater models are typically applied to single catchments and may not be suited to regional analysis. Coastal environments are difficult to characterise with a model, because groundwater inflows might be coming from a large upland area.

Recommendation:

It is recommended that the simple GIS approach be applied to estimate groundwater flow. These methods are not required for inland catchments.

Estimates of groundwater–marine interaction are likely to be very approximate, and calculated groundwater discharge volumes may be able to achieve only an order-of-magnitude accuracy at a regional scale (e.g. for any stretch of coastline 100 km long).

3.5.7 Extraction from groundwater to surface water

Extraction from a groundwater system is usually applied to the land surface as irrigation or enters the Water transport system (e.g. as urban water supply). However, groundwater could be pumped to a farm dam storage (to Surface water store) for later use.

Data will be provided through the Water Regulations for groundwater extraction. A methodology for estimating non-metered groundwater use in this context will also be required.

Recommendation:

It is recommended that data as supplied under Category 6e and 7b of the Water Regulations data be used (see Appendix A). The methodology for estimating non-metered groundwater use will also be required.

3.6 Water transport system storage and fluxes

3.6.1 Water transport system storage (store)

In simple terms, the Water transport system is the system of pipes and channels that is used to move water for human consumption or use (e.g. rural irrigation); water is usually moved in a direction in which it would not naturally flow (this includes interbasin transfer).

In the conceptualisation of a water balance, representation of the Water transport system may be considered to be part of the Surface water store, but separating the Water transport system facilitates the representation of urban water supply (e.g. in Figure 5, water flow for human consumption flows from 2. Surface water store to 4. Water transport system and then partly returns from 4. to 2. as wastewater. It also provides a useful collation of the water fluxes diverted for human use. This definition is applied rigidly so that e.g. water taken from farm dams passes into the Water transport system and is then used for irrigation; water pumped from groundwater and used directly in irrigation is also assumed to pass through the Water transport system. Note also that all 'inter-basin transfers' are considered to occur through the Water transport system.

The Water transport system holds a water volume that can be represented as unchanging; thus there is no 'change in storage' calculation required, although leakage and seepage are allowed for. Because there is no significant change in storage and often no significant loss, water flow components passing through the Water transport system can be labelled according to their destination. For example, an interbasin transfer into a reservoir within the catchment can be labelled as 'interbasin transfer to surface water store' and will appear as both an inflow and an outflow in the Water transport system.

3.6.2 Interbasin transfer (flux: from outside subcatchment)

Interbasin transfer (from outside subcatchment) is defined for the purposes of the water balance framework as 'the volume of water imported directly into the Water transport system from outside the defined water balance region or catchment. These imports may include inter and intra-company transfers'. Interbasin fluxes from outside the water balance region may remain in the Water transport system for direct use or may be directed as an outflow to the Surface water store, as defined in Section 3.4.17.

Recommendation:

It is recommended that data supplied under Category 7a of the Water Regulations be used (see Appendix A); these data will include water extracted from the Surface water store for export out of the water balance domain, as well as water extracted for use

within the domain. Category 7l and 7m of the Water Regulations (see Appendix A) will provide additional information relating to the volume of water exported to other infrastructure operators, inside and outside the water balance domain. It is not clear at this stage whether specific volumes, locations and details of the recipient operator, or water balance store, can be explicitly identified from the Water Regulations data described above. Determination of this component may rely on direct communication with the relevant data providers.

The Urban Water Calculator (Section 3.4.11), currently under development by the Bureau, can facilitate the aggregation of Category 7 Water Regulations data to the appropriate reporting unit for water balance purposes. The Calculator will identify interbasin water transfers from outside the water balance region, where supply networks cross over hydrological boundaries.

3.6.3 Marine desalination (flux: from outside subcatchment)

Marine desalination is defined for the purposes of the water balance framework as 'the volume of water provided to the Water transport system that is sourced solely from marine desalinisation'. This excludes desalinated groundwater extractions. This term represents desalinated water used directly to provide water supply to customers and excludes desalinated water transferred to surface water storage, which is defined in Section 3.6.17.

Recommendation:

Population of this component will use data supplied under Category 7c of the Water Regulations data (see Appendix A).

3.6.4 Inputs to Water transport system from Surface water store

The following inputs to the Water transport system (Table 5) are discussed as outputs from the Surface water store:

- bulk urban water (see section 3.4.11)
- bulk rural irrigation (see section 3.4.12)
- private irrigation (see section 3.4.13)
- private stock and domestic (see section 3.4.14)
- for Interbasin transfer – out (see section 3.4.17)
- private commercial/industrial diversions (see section 3.4.15)
- usage from private storage (see section 3.4.16).

3.6.5 Direct extractions from groundwater (flux: from Groundwater store)

Direct extraction from groundwater is defined for the purposes of the water balance framework as 'the volume of water extracted to the Water transport system from groundwater sources, including the volume originating from artificial recharge and desalinated groundwater'. Where possible, the volume of groundwater supplied will be categorised on the basis of the recipient users, including urban, irrigation, commercial/industrial and stock and domestic use. The ability to break down these data into this level of detail is heavily dependent upon the format of the Water Regulations data received and the availability of other data sources.

Data will be provided through the Water Regulations for groundwater extraction volumes. A methodology for estimating non-metered groundwater use in this context will also be required.

Recommendation:

Groundwater extraction data will be provided directly under Categories 7b and 5h of the Water Regulations data (see Appendix A). This will not cover all groundwater abstraction within the water balance regions; therefore, the additional volume, including non-metered groundwater use, will need to be estimated by using the approaches described in Appendix F for the relevant water users. Identification of non-metered groundwater users may be possible by using category 6e of the Water Regulations data (see Appendix A).

3.6.6 Water for interbasin transfers

The following inputs to the Water transport system from groundwater (Table 5) are discussed as an output from the Groundwater store:

- for interbasin transfers – out (see section 3.4.17).

3.6.7 Marine outflow of wastewater/effluent (flux: exiting subcatchment)

For the purposes of the water balance framework, outflow of wastewater/effluent is defined as 'the volume of wastewater, not including recycled water, which is transferred across the catchment boundary, including wastewater discharged from sewage treatment plants to marine waterbodies'. This term is differentiated from wastewater discharges within the water balance domain that provide a volumetric input to the Surface water store (see Section 3.6.16).

Recommendation:

Data will be provided through Category 7n of the Water Regulations data by the relevant providers for all outflow of wastewater to marine waterbodies and for wastewater exported to other infrastructure operators.

The Urban Water Calculator (Section 3.4.11), currently under development by the Bureau, can facilitate the aggregation of Category 7 Water Regulations data by the appropriate reporting unit for water balance purposes. The Calculator will identify marine outflow of wastewater/effluent.

3.6.8 Evaporation from irrigation channels (flux: exiting subcatchment)

For the purposes of the water balance framework, evaporation from irrigation channels (exiting subcatchment) is defined as 'the amount of water that evaporates from open channels that are used to supply irrigation demands'.

This will be estimated as evaporation from open water (See Section 3.4.7 on evapotranspiration).

3.6.9 Interbasin transfer (flux: exiting subcatchment)

Interbasin transfer (exiting the subcatchment) is defined for the purposes of the water balance framework as 'the volume of water, including recycled water, exported from the water transport system to outside the defined water balance region or catchment. These exports may include inter and intra-company transfers'. Interbasin fluxes to outside the water balance region may remain in the recipient area Water transport system for direct use or may be directed as an outflow to the Surface water store, as defined in Section 3.4.17.

Recommendation:

It is recommended that data supplied under Category 7a of the Water Regulations be used (see Appendix A); this will include water extracted for export out of the water balance domain as well as water extracted for use within the domain. Categories 7l and 7m of the Water Regulations (see Appendix A) will provide the volume of water exported to other infrastructure operators, inside and outside the water balance domain. It is not clear at this stage whether specific volumes, locations and details of the recipient operator or water balance store can be explicitly identified from the Water Regulations data described above. Determination of this component may rely on direct communication with relevant data providers.

The Urban Water Calculator (Section 3.4.11), currently under development by the Bureau, can facilitate the aggregation of Category 7 Water Regulations data by the appropriate reporting unit for water balance purposes. The Calculator will identify interbasin water transfers from inside the water balance region, where supply networks cross over hydrological boundaries.

3.6.10 Water use – rural irrigation (flux: to Landscape water store)

For the purposes of the water balance framework, water use – rural irrigation is defined as 'the volume of water that is used by irrigation and agricultural practices, which is in excess of the relevant crop water requirements and reaches the Landscape water store'. Data relating to irrigation water use will be provided through the Water Regulations by the relevant providers for water supplied to some irrigation districts and additionally for individual extractions/diversions, but there will be a significant proportion of properties that are non-metered for which estimates may need to be derived. Rural irrigation water use is directly related to the rural irrigation diversion and extraction terms defined in Section 3.4.12 and 3.4.13 but will represent the volume at the point of use, i.e. excluding losses through transmission and conveyance.

Recommendation:

It is recommended that data as supplied under Category 5 (all) and 6 (all) of the Water Regulations be used (see Appendix A) and that estimates be derived for areas that are non-metered. Rural irrigation water use will be derived from Categories 5d and 5e of the Water Regulations, but where these data are not available, or lack sufficient quality, it may be possible to calculate the water use on the basis of Categories 5a and/or 5h, applying assumptions for losses between extraction and use. Water use for non-metered sites, or for those not covered by the Water Regulations, will be estimated by using the approaches defined in Appendix F. It is also noted that methods for water-use estimation are being developed as part of the WIRADA WRAA project (Shao et al., 2008).

3.6.11 Water use – urban irrigation/outdoor (flux: to Landscape water store)

For the purposes of the water balance framework, water use – urban irrigation/outdoor is defined as 'the volume of urban water supply that is deemed to have been used for outdoor irrigation and other purposes, primarily garden water use within the urban context'. This represents a flux of water feeding into the Landscape water store. Outdoor water use within the urban context will be sensitive to the level and definition of any water restrictions imposed within the water balance region.

There is no existing direct data source or current means of reliably estimating this term. Residential water use (indoor and outdoor combined) will be provided under Category 7h of the Water Regulations data (see Appendix A). Other urban water-use categories – particularly municipal applications – are likely to also have an outdoor water usage component.

The urban irrigation and outdoor water-use component could be roughly estimated by applying an assumption about the percentage of water use that is used outdoors in a given urban area, and its average seasonal distribution, on the basis of the experience of the region's water authorities. However, it is expected that this would cause large errors and uncertainty, especially during periods of water restriction. It would also generate errors if water-use estimates were attempted at a monthly scale, because this component of water use is strongly influenced by weather conditions. [Note that whenever historic seasonal water-use patterns are used it is important to identify the level and nature of water restriction that may be in place.]

Depending on the quality of data provided under Categories 7h, 7i and 7j of the Water Regulations, it may be possible to estimate outdoor water use by examining the seasonal or monthly pattern of the residential, commercial, industrial and municipal and other water-use sectors. Winter season water use could be used to represent the non-seasonal, base level of water use (sometimes referred to as indoor water usage). Water use above this base level is then assumed to represent outdoor water use. However, this method relies on the region having a strongly seasonal outdoor water usage pattern, an assumption that does not hold across the country.

More consideration about the most appropriate method for calculating this water balance term is required, in light of the learnings gained from using the historic urban water usage data provided under Category 7 of the Water Regulations.

Recommendation:

In the first instance, it is recommended that the method of determining a non-seasonal baseline water usage rate for a given year and then assigning all water usage above this baseline to 'urban irrigation and outdoor' use be applied. Then, during the pilot water balance studies, more robust methods for calculating this term should be investigated and applied.

3.6.12 Wastewater/recycling for irrigation/outdoor (flux: to Landscape water store)

Wastewater/recycling for irrigation/outdoor use is defined for the purposes of the water balance framework as 'the volume of recycled/treated wastewater provided to irrigation, residential and non-residential customers for the purpose of irrigation and outdoor use'. This represents a flux of water feeding into the Landscape water store of the water balance and may be inherently related to the urban irrigation/outdoor water-use term described in Section 3.6.11.

Recommendation:

It is recommended that data as supplied under Categories 7d, 7h, 7i and 7j of the Water Regulations be used where possible (see Appendix A). Alternatively, the Essential Services Commission (ESC) or Water Services Association of Australia (WSAA) annual reports that provide an appropriate breakdown of figures could be used.

Data will be provided through the Water Regulations by the relevant providers of recycled water. However, it may be difficult to break down these data into specific amounts for irrigation and outdoor use, because the data are supplied under Categories 7h, 7i and 7j, all of which include potable and non-potable water supply lumped together (including recycled water). Other Water Regulations data that may be useful in estimating wastewater/recycling for irrigation/outdoor use include 7d and 7e, which respectively refer to the amount of recycled water produced internally and purchased externally by water utilities. However, these data may not necessarily be aligned with what has been supplied to customers.

3.6.13 Seepage from septic tanks (discharge from on-site sewage treatment) (flux: to Landscape water store)

Seepage from on-site wastewater treatment systems, including septic tanks, is defined for the purposes of the water balance framework as 'the volume of water entering the land and Surface water store as a consequence of seepage from septic tank and other on-site waste treatment processes'.

There is no direct data provision under the Water Regulations for seepage from septic tanks and on-site treatment processes and, in general, there is a sparse amount of information available for estimating this term.

One possible method would be to estimate the levels of internal water end-use of the properties that generate sewage, along with the number of properties in the region, to estimate the total volume of seepage from on-site sewerage systems. However, provision for the related required information about the number of septic tanks within a specific area is not included within the current Water Regulations. A targeted literature review and discussions with water utilities will be conducted to enhance the knowledge base within the Bureau.

Recommendation:

It is recommended that estimates of levels of indoor water use and the number of properties be used to calculate this term in the first instance. Discussions with water providers and other relevant parties may allow refinement of the inputs used to estimate this term in some areas. If no data or information is available this term may be left blank.

3.6.14 Water transport system leakage (flux: to Landscape water store)

Water transport system leakage is defined for the purposes of the water balance framework as 'the volume of water that leaks from the Water transport system into the Landscape water store, be it through a network of open channels or pipes that are under the ground'. Water transport system leakage represents the transmission and conveyance losses occurring between the point of abstraction and the point at which the final water use occurs. It may not be possible to disaggregate leakage losses from losses through other causes such as theft, illegal use and operational and fire use.

Recommendation:

Data will be provided through the Water Regulations Category 7j (see Appendix A) and will represent the volume of the non-revenue component of water supply, which includes leakage. There is no current method of estimating the leakage component of non-revenue water. Possible sources of information may include specific literature pertaining to water transport system leakage, which may then be used to apply a broad assumption; however this will assume little or no spatial variation in leakage. Leakage may be determined through conversations and consultation with water providers and utilities, or alternatively the leakage term may be inferred from the relevant ESC annual Water Performance Report, and the WSAA annual National Performance Reports.

3.6.15 Seepage from irrigation channels (flux: to Landscape water store)

See section 3.5.4 for surface–groundwater interactions, including estimation of seepage from irrigation channels.

3.6.16 Urban wastewater/effluent (flux: to Surface water store)

Urban wastewater/effluent to the Surface water store is defined for the purposes of the water balance framework as 'the volume of sewage, not including recycled water, which is discharged from sewage treatment plants to surface water features within the water balance domain'. This does not include wastewater or effluent discharged to the marine environment or exported out of the water balance region, as defined in Section 3.6.7.

In light of the wording of 7n in the Water Regulations (see Appendix A), it is likely that some, or most, data providers will provide the Bureau with monitored discharges from a 'sewage discharge point to a watercourse' only. As many of these discharge points may not be monitored, and the data provider may interpret the data request as relating only to sewerage system overflow points, rather than more broadly including discharges from wastewater treatment plants, it is anticipated that, in the first instance, the data coverage of this term will be patchy.

Recommendation:

It is recommended that data as supplied under Category 7n of the Water Regulations data (see Appendix A) be used. Once an understanding of the 7n data provided by the urban water utilities has been gained, consideration will be given to rewording the definition of 7n in the Water Regulations to better capture the Bureau's data requirements.

The Urban Water Calculator (Section 3.4.11), currently under development by the Bureau, can facilitate the aggregation of Category 7 Water Regulations data by the appropriate reporting unit for water balance purposes. The Calculator can identify wastewater/effluent discharge to waterways.

3.6.17 From marine desalination (flux: to Surface water store)

From marine desalination is defined for the purposes of the water balance framework as 'the volume of water taken from marine desalination, excluding desalinated groundwater, which is transferred via the Water transport system to storage within the Surface water store'. This excludes desalinated water supply for direct consumption, as defined previously in Section 3.6.3.

Data will be provided through the Water Regulations by the relevant providers for all marine desalinated water.

Recommendation:

It is recommended that data as supplied under Category 7c of the Water Regulations data (see Appendix A) be used. It is not clear whether the data provided under Category 7c will explicitly define the recipient store of the desalinated water supply, i.e. direct water use or transfers to storage reservoirs. This will need to be clarified through consultation with the relevant data provider.

3.6.18 Interbasin transfers, in (flux: to Surface water store)

For the purposes of the water balance framework, Interbasin transfers, in (to Surface water store) are defined as 'the volume of water, not including recycled water or wastewater, that crosses the catchment boundary as an import through the Water transport system and is transferred to the Surface water store'. This term may need to be differentiated from the flux to surface water from marine desalination.

Data will be provided through the Water Regulations by the relevant providers for all transfers to water storages (3d) and for exports to other utilities (7l and 7m). It will be difficult to obtain the figures for water transfers across the catchment boundary if the water remains within the jurisdictional boundary of an organisation when that boundary

overlaps with the catchment boundary. Therefore, direct consultation with the water utilities may be required.

Recommendation:

It is recommended that data as supplied under Categories 3d, 7e and 7f of the Water Regulations data (see Appendix A) be used. Discussions with water providers and utilities, in combination with review of the relevant annual reports (where feasible), may help to provide figures where organisational boundaries overlap the catchment boundary.

3.6.19 Rural irrigation returns (flux: to Surface water store)

For the purposes of the water balance framework, rural irrigation returns are defined as 'The volume of water returned to the Surface water store from an irrigation network or individual irrigator'. This represents the unused or excess volume of irrigation extractions or provisions or returns collected through irrigation drainage systems.

Recommendation:

It is recommended that data supplied under Category 5b (to a watercourse), 5c (to a water storage), and 5i (individual irrigator returns) of the Water Regulations be used. There are no defined estimation methods for irrigation return flows; therefore, extrapolation of this component may be based on available research and studies where possible, or inferred from the available Water Regulations data (i.e. returns are, on average, x% of irrigation water use). However, it may be more prudent to assume no return flows where no data exists. Information on the sensitivity of the balance, as well as uncertainty estimates, may be required.

3.6.20 Leakage/seepage from irrigation channels and urban supply (flux: to Groundwater store)

Leakage/seepage from irrigation channels and urban supply is defined for the purposes of the water balance framework as 'the volume of water that leaks from the irrigation and urban water transport systems into the Groundwater store, be it through a network of open channels or pipes that are under the ground'. This term is directly related to the similar flux to the Landscape water store (Section 3.6.15), and the allocation of these losses to the individual stores may be difficult to calculate.

Recommendation:

Volumes of leakage and seepage from irrigation channels and urban supply pipes will be assessed by the same methods as those described in Section 3.6.14 above. The assessed losses will need to be appropriately allocated to the respective recipient stores.

4 Conclusion

Methods of populating terms of the water balance framework have been reviewed. For each component of the detailed water balance framework, a method has been recommended for use within the pilot water balance studies to be carried out by late 2009/early 2010. It is noted that the methods have been chosen on the basis of what is applicable currently (as opposed to the methods being developed within WIRADA) within the time frame available.

Although internal consistency, uncertainty estimation and reconciliation of multiple sources of information are recognised as desirable attributes of the component methodologies, the main aim of the review was to recommend methods that could be applied by late 2009 for a series of regional studies. Further work is required in these areas once population of the water balance has been trialled within the pilot studies.

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Appendix A The Water Regulation Data

Table 8. Water data to be supplied as part of the Water Regulations (source: www.bom.gov.au/water/regulations).

Category	Description
Watercourses	1a: Instantaneous watercourse level (expressed in metres relative to specified datum), and the time of the observation 1b: Instantaneous watercourse discharge (expressed in cumecs), and the time of the observation
Groundwater	2a: Groundwater level of a bore (expressed in metres relative to specified datum), and the time of the observation 2b: Groundwater pressure of a bore (expressed in kilopascals), the aquifer layer and depth at which the pressure is measured, and the time of the observation
Levels and volumes	3a: Level of water held in a major storage (expressed in metres relative to specified datum), and the time of the observation 3b: Volume of water held in a major storage (expressed in megalitres), and the time of the observation 3c: Total daily volume of water released from a major storage to a watercourse (expressed in megalitres per day), the start and finish times of the observation, and the date of the observation 3d: Total daily volume of water transferred between major storages (expressed in megalitres per day), the start and finish times of the observation, and the date of the observation 3e: Volume of water held in a minor storage (expressed in megalitres), and the time of the observation 3f: Information in registers of major storages and information about dams prescribed under dam safety regulations as referable dams, including the location, dimensions, capacity, ownership and owner's contact details for major storages and for referable dams
Metrological information	4a: Accumulated precipitation depth for a specified time interval (expressed in millimetres), and the time of the observation 4b: Instantaneous wind speed (expressed in metres per second), wind direction, and wind run (expressed in kilometres over a specified period), and the time of the observation 4c: Total daily evaporation from a Class A evaporation pan (expressed in millimetres per day), the start and finish times of the observation, and the date of the observation 4d: Global solar exposure, reflected global solar exposure, downward longwave exposure, upward longwave exposure, and net exposure. 4e: Global solar irradiance, reflected global solar irradiance, downward longwave irradiance, upward longwave irradiance, and net irradiance. 4f: Instantaneous dry-bulb air temperature (expressed in degrees Celsius), and the time of the observation 4g: Instantaneous wet-bulb air temperature (expressed in degrees Celsius), and the time of the observation 4h: The instantaneous relative humidity (expressed as a percentage), and the time of the observation 4i: The instantaneous vapour pressure deficit (expressed in millibars), and the time of the observation

Category	Description
Water-use information	5a: The total daily volume of water diverted from a watercourse to an irrigation network (expressed in megalitres per day), the start and finish times of the observation, and the date of the observation 5b: The total daily volume of water returned to a watercourse from an irrigation network (expressed in megalitres per day), the start and finish times of the observations, and the dates of the observations 5c: The total daily volume of water returned to a water storage from an irrigation network (expressed in megalitres per day), the start and finish times of the observations, and the dates of the observations 5d: The total daily volume of water supplied to all irrigators in an irrigation network (expressed in megalitres per day), the start and finish times of the observations, and the dates of the observations 5e: The total monthly volume of water supplied to individual irrigators in an irrigation network (expressed in megalitres per month), the start and finish times of the observations, and the dates of the observations 5f: The total monthly volume of water taken by individual self-extractors (expressed in megalitres per month), the start and finish times of the observations, and the dates of the observations 5g: The total monthly volume of water taken from a watercourse by self-extractors (expressed in megalitres per month), the start and finish times of the observations, and the dates of the observations 5h: The total monthly volume of water extracted from a bore by self-extractors (expressed in megalitres per month), the start and finish times of the observations, and the dates of the observations 5i: The total monthly volume of water a self-extractor returns to a watercourse (expressed in megalitres per month), the start and finish times of the observations, and the dates of the observations
Information about rights, allocations and trades in relation to water	6a: For Australian water access entitlements: the type, the volume of water, and the water management area in which the entitlement exists 6b: For permanent Australian water access entitlement trades: type of entitlement traded, transaction commencement and finalisation dates, volume of water traded or entitlement share traded, gross and net share sale prices, and water management areas water has moved from and to 6c: For temporary Australian water allocation trades and leases: the type of allocation traded or leased, transaction commencement and finalisation dates, volume of water traded or leased, gross and net sale price, and water management areas water has moved from and to 6d: For formal announcements of Australian water allocations made to Australian water access entitlements and formal announcements of reductions to allocations already made: a copy of the announcement, plus details of the water management area to which the allocation announcement applies and the type of entitlement affected 6e: For a permit to operate a minor storage: the location of the storage and the maximum permissible storage volume 6f: For a permit to self-extract water from a bore: the location and permitted depth of the bore, the maximum permissible extraction volume and any other conditions of use 6g: For a permit to self-extract water from a watercourse: the location of the extraction point, the maximum permissible extraction volume, and any other conditions of use.

Category	Description
Information about urban water management	7a: The total weekly volume of water taken from surface water (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7b: The total weekly volume of water taken from groundwater (expressed in megalitres per week)the , the start and finish times of the observations, and dates of the observations 7c: The total weekly volume of water taken from desalination (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7d: The total weekly volume of water taken from recycling (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7e: The total weekly volume of water received from infrastructure operators (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7f: The total weekly volume of bulk recycled water purchased (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7g: The total weekly volume of water taken (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7h: The total weekly volume of residential water supplied (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7i: The total weekly volume of commercial, municipal and industrial water supplied (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7j: The total weekly volume of water supplied, other than residential, commercial, municipal and industrial water (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7k: The total weekly volume of urban water supplied (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7l: The total weekly volume of bulk water exports (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7m: The total weekly volume of bulk recycled water exports (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7n: The total weekly volume of sewage discharges from a sewage discharge point into a watercourse (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations 7o: The total weekly volume of stormwater discharges from a stormwater discharge point into a watercourse (expressed in megalitres per week), the start and finish times of the observations, and the dates of the observations
Information about water restrictions	8a: Water-use restriction announcements giving level, commencement and termination dates, as well as a description of water restriction levels and where they apply: definitions for each restriction level, the water savings target and the geographic area in which the restriction conditions apply (so that the area can be accurately mapped)

Category	Description
Water quality information	9a: The instantaneous electrical conductivity of a water sample collected above the tidal limit of the watercourse (expressed in microsiemens per centimetre at 25°C), and the time of the observation 9b: The instantaneous electrical conductivity of a groundwater sample collected above the tidal limit of the watercourse (expressed in microsiemens per centimetre at 25°C), and the time of the observation 9c: The instantaneous total suspended solids concentration of a water sample collected above the tidal limit of a watercourse (expressed in milligrams per litre), and the time of the observation 9d: The instantaneous turbidity of a water sample collected above the tidal limit of a watercourse (expressed in nephelometric turbidity units), and the time of the observation 9e: The instantaneous total phosphorus concentration of a water sample collected above the tidal limit of a watercourse (expressed in milligrams per litre), and the time of the observation 9f: The instantaneous total nitrogen concentration of a water sample collected above the tidal limit of a watercourse (expressed in milligrams per litre), and the time of the observation 9g: The instantaneous pH of a water sample collected above the tidal limit of a watercourse, and the time of the observation 9h: The instantaneous temperature of a water sample collected above the tidal limit of a watercourse (expressed in degrees Celsius), and the time of the observation
Descriptive and reference information about water information in other categories	10a: Tables that enable the derivation of volumetric flow from water level or stage height: the complete historical sequence of rating tables, indicating the time span across which the rating should apply 10b: Rating tables for the surface area and storage volume derivation of major storages: the complete historical sequence of rating tables, relating major storage water level to reservoir surface area and storage volume, indicating the dead storage level and volume, and indicating the time span across which the rating should apply 10c: Description of Australian water access entitlements: the name of the entitlement, its reliability and security characteristics, any special conditions that apply to it, and the geographic area in which the entitlement is valid, described so that it can be accurately mapped 10d: Description of all water management areas: the name of the water management area and a description so that it can be accurately mapped 10e: Metadata about other water information 10f: Manuals or protocols that describe procedures used in measuring, managing or interpreting water information

Appendix B Evapotranspiration estimation

B.1 Definition of terms

Potential Evaporation

Potential Evaporation (PE) is the evaporation that would occur with an unlimited water supply. PE methods appropriate for estimating evaporation from open waterbodies are the focus of this PE methods review.

Potential evapotranspiration (PET)

Potential evapotranspiration (PET) is the evapotranspiration that would occur with an unlimited water supply. PET is not used directly in the water balance calculations, but it is used as a model input for rainfall–runoff models for runoff estimation.

Actual evapotranspiration (AET)

Actual Evapotranspiration (AET) is the ET that actually takes places in the landscape, given actual moisture and energy conditions. AET is used to assess the volume of water lost to ET from the landscape, including under different land uses.

B.2 Potential evaporation (PE)

B.2.1 Bureau of Meteorology gridded average monthly and annual potential evaporation – climatology based on 1961–1991

The average annual and monthly potential evaporation datasets provided by the Bureau constitute a basic representation of the spatial variation in evaporation across Australia. The mean data are based on all available stations with at least 10 years of records between 1975 and 2005 – in total, 270 stations. Of these stations over 80% had a complete dataset for the analysis period. The mean monthly and mean annual evaporation grids show evaporation values in the form of two-dimensional array data. Gridded data are generated from the Bureau's Class A pan evaporimeters observations by using the Barnes 2-D meteorological analysis (Mills et al., 1997; BoM, 2008).

B.2.2 SILO daily surfaces

SILO is provided by the Queensland Department of Natural Resources and Water (DNRW). There are two products available from SILO. The first is a surface based on interpolation of the Bureau's Class A pan evaporation stations records, which dates back to 1970 and relies on long-term means before this. The other surface is a synthetic daily Class A pan evaporation dataset calculated by using the SILO climate gridded products. Both datasets are potential evaporation and are available in gridded format (Davie et al., 1989; Davis et al., 2001; de Vries and Simmers, 2002).

Interpolated Class A pan evaporation surfaces

Point data: SILO provides time-series point potential evaporation data for approximately 4600 stations across Australia. The patched datasets have been constructed from data recorded from Class A pans that measure potential evaporation. The data are patched by using the interpolated surface data. These data are reliably available only post 1970. For dates preceding 1970, the patched datasets have been supplemented with daily long-term means for pan evaporation (Jeffrey et al., 2001).

Gridded data: SILO also provides a gridded daily potential evaporation dataset produced through interpolation of the point data. The Class A pan evaporation data are interpolated by using a trivariate thin-plate smoothing spline (Wahba and Wendelberger, 1980), with latitude, longitude and elevation as independent variables. The surfaces were fitted by

minimising the Generalised Cross Validation (CV) error with the constraint of first-order smoothness imposed (Jeffrey et al., 2001).

To identify and remove erroneous data, the interpolated surfaces were constructed by using a two-pass interpolation scheme. Observed data were interpolated in a first pass, and the residuals – the differences between the observed and interpolated values – were computed for all data points. Data points with residuals greater than 2.7 mm pan evaporation were considered indicative of erroneous data and excluded from subsequent interpolation; the remaining data was then used to generate the final surface of gridded potential evaporation (Jeffrey et al., 2001). Data points with residuals greater than 2.7 mm constitute approximately 1% to 2% of the data. The final gridded product is available on a daily time-step for the period of 1957 to the present on a 0.05° (~5-km) national grid.

Cross-validation was completed on the gridded products and error statistics analysed on a spatial and temporal scale. The error surfaces could possibly be used in uncertainty reporting.

Australian synthetic daily Class A pan evaporation

The second SILO product is a synthetic, daily Class A pan evaporation dataset for Australia for the period 1910 to the present. The main advantage of this product is that it provides a longer record of gridded evaporation data. As potential evaporation is calculated from the other SILO climate datasets, daily gridded surfaces can be generated for as far back as there are reliable climate data. This product is generally designed to replace the use of the long-term average monthly datasets. As it is calculated on the basis of the SILO climate datasets it is available on the same spatial scale of a 0.05° (~5-km) grid. It is available on a daily basis for the period of 1910 to the present, but the accuracy of the grids is lower in the pre-1957 period.

The synthetic pan evaporation model is a spatially and seasonally varying, empirical model. It is a simple linear combination of gridded solar radiation and vapour pressure deficit (see below). The regression coefficients are determined independently for each pixel of the standard SILO pan evaporation surfaces, and separately for each month for the period 1975–2003. Considering the grids and months independently eliminates regional and seasonal bias, but at the cost of capturing regional climate variability and climate change (Rayner, 2005).

Gridded Class A Pan evaporation was modelled as:

$$E_{pan} = b \times R_s + c \times (e_s \times e_a) \qquad \textbf{Equation 1}$$

where:

E_{pan} = gridded Class A pan evaporation rate [mm day^{-1}],

R_s = gridded daily total solar radiation [MJ m^{-2} day^{-1}],

e_s = gridded mean daily saturation vapour pressure [hPa],

e_a = gridded 9 am vapour pressure [hPa], and

b,c = empirically-derived coefficients.

The parameters b and c in Equation 1 are the coefficients that were fitted for each pixel in the 0.05º (~5-km) grid by using multiple regression using daily data from 1975–2003 inclusive (Rayner, 2005).

The term $(e_s \times e_a)$ in Equation 1 is known as the vapour pressure deficit.

The mean daily saturation vapour pressure is estimated as (Jeffrey et al., 2001):

$$e_s = 0.75e^0(T_{max}) + 0.25e^0(T_{min})$$ **Equation 2**

where:

$e^0(T)$ saturation vapour pressure at air temperature T, given by (Allen et al., 1998)

$$e^0(T) = 0.6108\exp\left(\frac{17.27T}{T + 237.3}\right)$$ **Equation 3**

All of the observed data required for the model were supplied by the Bureau and collected or generated by the following means:

- Minimum and maximum daily temperatures and pan evaporation were recorded directly by observers. The temperature grids were then defined according to the same method as the SILO pan evaporation grids (outlined in B.2.2).
- Vapour pressure deficit grids were calculated by using the SILO maximum and minimum temperature grids to estimate daily-average saturation vapour pressure, and by using the SILO 9 am vapour pressure grids to approximate the daily-average actual vapour pressure (Rayner, 2005).
- Daily solar radiation records were derived from total cloud amounts, supplied in oktas.

Rainfall is incorporated into the synthetic pan model implicitly through its relationship with solar radiation and vapour pressure (Rayner, 2005). This, however, does not mean that moisture availability is inbuilt: the results still represent an estimate of potential evaporation, not actual.

The reason the model is based on the gridded climate datasets rather than the observation points is that the majority of daily climate observing stations do not have an evaporation pan. The model takes advantage of the high-spatial-resolution climate data provided by the full network of stations by using the gridded products (Rayner, 2005). This method does potentially introduce error through the interpolation of the sparser evaporation station network for the calibration surfaces, but this error would have been introduced in interpolating the model results if modelling were completed only at the observation points.

The observed pan evaporation data used to produce the gridded surface was used to validate the model. Only stations with evaporation records for at least 50% of the days in the period 1975–2003 were used. The synthetic pan evaporation is produced on the basis of the relationship between the gridded pan evaporation, which is produced from the observed values, and the gridded climate datasets. The synthetic values are then finally compared with the observed values for validation. In this sense the observed values are not an independent validation dataset (Rayner, 2005).

Advantages

Rayner (2005) suggested the following advantages over the long-term averages:

- Has some representation of observed daily pan evaporation variability:
  - The long-term average does not really represent daily variation in evaporation at all.
- Has improved overall accuracy:
  - The mean absolute error calculated with reference to the validation dataset is lower for the synthetic dataset than for the long-term average datasets.
  - For both datasets, the errors are highest in inland areas in December–February, when the evaporation rates are highest.
- Preserves the natural inter-correlations within the climate dataset (especially the relationship with rainfall):

  - The synthetic pan model represents the decrease in pan evaporation after significant rainfall quite well, whereas the long-term average does not take into account the lower evaporation likely following a rain event (high humidity and cloud).

It avoids some of the errors associated with observed data, such as:

- Pan evaporation records contain unrealistically high values, often associated with high rainfall.
- Many pan evaporation observations are rounded to the nearest 4 mm.

Disadvantages/limitations

With reference to the observed pan evaporation record:

- The synthetic pan evaporation model does not utilise wind information, which can have an important effect on evaporation.
- Errors are biggest on very windy days.
- The model underestimates very high and very low evaporation rates.
  - This is likely due to the lack of wind in the model; very high evaporation rates are associated with high winds. The over and under estimation could be associated with the smoothing effect of the spline function. Solar radiation values are smoothed by the use of cloud levels at 9 am and 3 pm only.
- The model does not represent climate trends.
- The model does not replicate trends in observed post-1970 pan evaporation.
- Because the model is spatially and seasonally dependent, it will not be robust against climate variability or climate change.
- Variables beyond those captured in the model may have changed. The trend changes may be in the extreme evaporation values that are not represented well by the model.
- Trends that are also represented in the temperature and rainfall will be represented in the evaporation results, but changes in evaporation that are not necessarily related to solar radiation or vapour pressure deficit will not be reproduced and represented in the final layers.

B.2.3 CSIRO national Penman-based potential evaporation datasets

National gridded potential evaporation datasets have recently been produced by CSIRO Land and Water in an attempt to calculate fully dynamical estimates of potential evaporation (Donohue et al., 2009). CSIRO Land and Water produced and compared a series of datasets on a 0.05° (~5-km) grid resolution by using a combination of satellite data, Bureau station point data, and a spatial dataset of windspeed produced by McVicar et al. (2008). The methods used to estimate potential evaporation included Penman, Penpan, FAO56 Reference, Priestly-Taylor, Palmer Drought Severity Index (PDSI), Morton's areal (wet environment) and Thornthwaite. Of these methods, Penman and Penpan were determined to be the most appropriate for estimating evaporation from open water. Priestly-Taylor, PDSI, Morton and Thornthwaite were not considered to be fully physical or fully dynamical models, because they do not incorporate all four drivers of evaporation that are incorporated into the Penman based methods (slope of the saturation vapour pressure curve, daily net radiation, vapour pressure deficit, and daily windspeed). These datasets are all available on a 0.05° national grid at a daily time-step from 1981–2006.

B.2.4 Other synthetic model options – potential evaporation

AussieGRASS is a synthetic pan evaporation model (reviewed by Rayner, 2005) that is available nationally and is based on the relationship between observed pan evaporation and climate data at selected Queensland rangeland locations. Like the SILO synthetic model, AussieGrass used multiple regression with climate variables, but the regression used an "ensemble" approach, using data from multiple sites to obtain a single set of regression coefficients. This method applied on a national scale is likely to introduce regional bias into the model.

B.3 Evaporation from open waterbodies

There are a number different ways to calculate evaporation from open waterbodies. Pan evaporation datasets can be used through the application of coefficients to account for the difference in Class A pans and larger waterbodies. Other techniques include the calculation of mass balances, energy budgets and bulk transfers, and various combinations of these calculations.

B.3.1 Murray-Darling Basin Sustainable Yields – evaporation from open water

The model

In the Murray-Darling Basin Sustainable Yields Project, water evaporation was estimated by using a 'combination method'. Combination methods combine the mass transfer and energy budget principles in a single equation (McJannet et al., 2008). The method used in this project used the Penman-Monteith equation, accounting for heat storage within the waterbody. The input parameters are net radiation, air temperature, vapour pressure and wind speed and an estimate of heat storage (McJannet et al., 2008). This method estimates an evaporation rate, but in order to convert this rate into a volume the area of each type of waterbody must be determined. The types considered in this project include irrigation channels (channels, drains and aqueducts), reservoirs, ponds, streams, lakes and areas inundated by floods. All waterbody types, except streams and flood areas, were considered constant in time owing to a lack of data on the other datasets. An assessment of the model uncertainty centred on the input parameters is provided by McJannet et al. (2008). The model uses readily available datasets. The primary source of the meteorological data was SILO, and the waterbody geometry was calculated as below.

The AET methods outlined in Section B.4.3 have also been shown to accurately estimate evaporation from large waterbodies, but the above method was used in calculating direct evaporation for the water balance accounts in the MDBSY project and is more appropriate for estimating evaporation from smaller waterbodies.

Waterbody area

All methods require an accurate estimate of at least the surface area of waterbodies. MDBSY reported that the calculations were most sensitive to errors in the surface water area, a parameter for which estimation of changes on an annual basis is difficult.

In the MDBSY, values were extracted for the area (or length) of each of the waterbody types from the GEODATA TOPO 250K Series 3 Topographic Dataset from Geosciences Australia (McJannet et al., 2008). Waterbody width and depth were estimated differently for irrigation channels, streams, reservoirs. These methods can be found in the work of Kirby et al. (2008). Stream areas were estimated by using the relationships between channel width, depth and discharge, and areas inundated by flood were determined by analysis of MODIS satellite images.

B.4 Potential evapotranspiration (PET)

B.4.1 Bureau of Meteorology monthly potential evapotranspiration – climatology based on 1961–1991

The Bureau produces gridded datasets of mean monthly and annual potential evapotranspiration. The mean data are based on the standard 30-year period of 1961–1991 and are available at a grid point resolution of 0.1° (approximately 10 km).

The Morton (1983) complementary relationship areal ET model was used to derive estimates of areal potential ET, point potential ET and areal and actual ET. Morton's method for point PET is based on solving simultaneous energy transfer and balance equations. Once the point and areal PET are estimated, the complementary relationship (model) can be used to give an estimate of the areal actual ET. The complementary relationship states that, under normal conditions, the sum of areal actual ET and point potential ET is equal to twice the value of areal potential ET. Morton's formulation for areal potential ET uses the Priestley-Taylor equation, with modification to allow for advection. Morton's method for point potential ET is based on solving simultaneously energy transfer and balance equations, using a constant energy transfer coefficient; this is unlike the Penman-Monteith potential ET formulation, in which the energy transfer coefficient is a function of wind speed (Wang et al., 2001).

The data inputs required by the Morton's (1983) complementary relationship model to estimate areal ET are temperature, vapour pressure and solar global radiation. Data from 713 meteorological stations were used. Only stations with at least 5 years' temperature and vapour pressure after 1961 were used. Daily mean temperature was taken as the average of daily maximum and minimum temperatures. Daily mean vapour pressure was taken as the average of vapour pressures, calculated from dry- and wet-bulb temperatures, at 0900 and 1500 hours (Wang et al., 2001).

Hutchinson's (1991; 1995) interpolation method of thin-plate smoothing splines was used to produce grid data at a 0.1° (~10-km) resolution. As part of the 3-D analysis process a 0.1°-resolution digital elevation model (DEM) was used. Elevation as well as latitude and longitude were used as explanatory variables to take into account the variation of precipitation, temperature and vapour pressure with elevation. The interpolated (gridded) data were then smoothed by using a one-pass 5 x 5 binomial smoother.

These datasets are generally used to produce the upper limit to actual ET in rainfall–runoff modelling. The climatological means are generally used for long-term modelling to provide estimates for periods before the observed potential evaporation. These datasets could be used in the trend analysis of water balance elements, but in estimating ET in a current annual or monthly water balance a dataset that provides some estimate of actual temporal variation would be more valuable.

B.4.2 Reference evapotranspiration (ETo)

ETo is a measure of PET over a standard grass surface and is widely recognised as the measure of PET most applicable to cropping and tactical irrigation decisions (Allen et al., 1998). It applies the Penman-Monteith method and recommends a series of default climatological values where data are not available. SILO produces a reference ETo on a national 0.05° (~5-km) grid, using the climatological default value for wind suggested in the FAO56 guidelines.

As outlined in Section B.2.3 (Donohue, In prep.) have also produced a FAO56 reference ETo, but they included the daily wind data produced by McVicar et al. (2008) instead of the default values. The datasets are available on a 0.05° (~5-km) spatial grid and a daily time step for 1981–2006.

The Penman-Monteith method used to estimate Reference FAO56 PET is outlined below:

$$E_o = \frac{\Delta R_r + 0.9\gamma u_2 D/T_a}{\Delta + (1 + 0.34u_2)\gamma}$$

Where:

γ = the psychrometric constant (Pa.K^{-1}),

D = vapour pressure deficit (Pa),

u_2 = daily average wind speed at 2 m elevation (m.s^{-1}),

Δ = is calculated as a function of saturated vapour pressure (e_s, Pa) and T_a, and

R_r (mm.day^{-1}) = net radiation calculated by using a constant α (0.23) and f_v (0.76). This value of f_v was obtained by converting the height of the reference surface of 0.12 m to a Leaf Area Index of 2.88 (Allen et al., 1998), which is then converted to f_v according to the method of Choudhury (1989).

B.5 Actual evapotranspiration

B.5.1 Bureau of Meteorology monthly actual evapotranspiration – climatology based on 1961–1991

Areal actual ET is estimated on the basis of the mean areal and point potential ET outlined in section B.4.1. Morton's method for point PET is based on solving simultaneous energy transfer and balance equations. Once the point and areal PET are estimated, the complementary relationship (model) can be used to give an estimate of the areal actual ET (Wang et al., 2001). These values are then adjusted on the basis of AET estimates derived from the long-term water balance of 77 large catchments grouped into nine climate zones. The mean monthly actual ET values are then proportionately adjusted according to the adjustments made to the mean annual actual ET values. The adjusted AET estimates are then interpolated by using thin-plate smoothing splines. The annual areal AET values were then compared with the latest available rainfall maps and adjusted to ensure that the annual areal AET did not exceed rainfall and that the runoff coefficients were reasonable (Wang et al., 2001).

B.5.2 Australian Water Availability Project (AWAP) – WaterDyn

WaterDyn is the water balance model developed by CSIRO for the Australian Water Availability Project (AWAP). It models the state of soil moisture and all water fluxes contributing to changes in soil moisture (rainfall, transpiration, soil evaporation, surface runoff and deep drainage). The model is spatially resolved across the Australian continent on a 5-km grid (Raupach et al., 2008). Key inputs and constraints on the model are the meteorology (solar radiation, precipitation, minimum and maximum daily temperatures) and continental parameter maps (e.g. albedo, soil characteristics, seasonality of vegetation greenness).

The soil moisture and fluxes are defined on two control volumes consisting of 'shallow' (typically to a depth of 0.2 m) and 'deep' (typically 0.2 to 1.5 m) soil layers. WaterDyn equates the changes in the soil water store in each control volume to the sum of the water fluxes across the boundaries of the volume, as follows (Raupach et al., 2008):

$$dW_1/dt = F_{WPrec} - F_{WTra1} - F_{WSoil} - F_{WRun} - F_{WLch1}$$

Change of soil water in layer 1	Precipitation	Transpiration from layer 1	Soil Evaporation	Surface Runoff	Leaching from layer 1 to 2

$$dW_2/dt = F_{WLch1} - F_{WLch2} - F_{WTra2}$$

Change of soil water in layer 2	Leaching from layer 1 to 2	Deep Drainage	Transpiration from layer 2

The blue and red identify input and output fluxes, respectively.

Total evapotranspiration – WaterDyn

Total evapotranspiration is the sum of transpiration and soil evaporation, as denoted by *FWE = FWTra + FWSoil*.

Transpiration (FWTra)

Transpiration occurs from both soil layers and is defined as the lesser of the energy-limited and water-limited transpiration rates.

The total **energy-limited transpiration rate** is the evaporation rate from surface without water constraints. In WaterDyn it is defined by the Priestley-Taylor evaporation rate attenuated by the vegetation cover term:

$$F_{WTra(ELim)} = vF_{W(PT)}$$

where *v* is the vegetation cover fraction (between 0 and 1) and *FW*(PT) is the Priestley-Taylor evaporation rate [m-water day^{-1}]. The *FW*(PT) term represents a thermodynamic estimate of the energy-limited evaporation rate for the whole surface (vegetation plus soil), but the inclusion of the *v* factor relates the evaporation to the plant component only (Raupach et al., 2008).

The **water-limited transpiration rate** in each soil layer is specified by using a rate parameter *kE*, which controls the decay of water extraction by roots from a drying soil under water-limited transpiration and full vegetation cover (Raupach et al., 2008):

$$F_{WTra(WLim)i} = vk_{Ei}W_i$$

The vegetation cover fraction *v* is included as a multiplier to scale the water extraction by the amount of vegetation present.

Essentially, evaporation is determined by water supply (rainfall) in dry environments and energy supply (radiation) in wet environments. Evaporation in dry environments is represented by the water-limited transpiration rate and in the wet environments by the energy-limited transpiration rate. To build a transpiration grid from these two terms, the single-parameter hyperbolic function interpolates between dry (water-limited) and wet (energy-limited) total evaporation rates. The value of this parameter describes the influence of catchment land characteristics on actual evapotranspiration (Raupach et al., 2008).

Estimating the vegetation fraction

The vegetation cover fraction (*v*) is given either externally or from a leaf carbon submodel. When externally prescribed, it is given by the smooth curve

$$v = \frac{1 - \exp(c_{PAR} FAPAR)}{1 - \exp(c_{PAR})}$$

where FAPAR is a remotely sensed Fraction of Absorbed Photosynthetically Active Radiation and c_{PAR} is a coefficient of order −2. FAPAR is the fraction of the incoming solar radiation in the photosynthetically active radiation spectral region that is absorbed by plants and can be directly related to the primary productivity of plants (Gobron et al., 2002). The SeaWiFS Vegetation Index is a derived FAPAR product available globally at ~0.04° (~4-km) spatial and monthly time resolution (Gobron et al., 2002), continuously from September 1997 to June 2006. It is resampled to 0.05° (~5-km) resolution and averaged to a monthly climatology for use in WaterDyn. Both v and FAPAR are constrained to the interval from 0 to 1.

In earlier versions (versions <21) of WaterDyn a leaf carbon model was used to determine v, but although the model produced a realistic long-term average it did not capture the correct amplitudes and phase of seasonal cycles, so the above remote-sensing methods is favoured in current versions.

Soil evaporation (F_{WSoil})

Soil evaporation is the product of an upper-limit value (Priestley-Taylor evaporation), the relative water content in the upper soil layer raised to power (a model parameter), and the fraction of bare soil (1 − v):

$$F_{WSoil} = (1 - v) w_1^{\beta} F_{W(PT)}$$

where β is an exponent specifying the response of soil evaporation to upper-layer soil water (w_1).

Summary of WaterDyn evapotranspiration products

AWAP provides the following variables on a ~5-km x 5-km (0.05°) national grid:

- Total Evaporation (Soil+Vegetation) (FWE) (0–6 mm/day)
- Soil Evaporation (FWSoil) (0–1.5 mm/day),
- Total Transpiration (FWTra) (0–4 mm/day)
- Potential Evaporation (FWPT) (0–10 mm/day).

The time steps publicly available are:

- weekly (2007 to ongoing)
- monthly (1900 to ongoing)
- annual (1900 to ongoing).

It is currently possible for the Bureau to get a daily time-step on request from the CSIRO, but this does require the model to be specifically run for periods on request.

Advantages

- AWAP provides a series of water balance variables that are physically consistent.
- The gridded products are available nationally and on an appropriate spatial scale to allow data on subcatchments to be extracted.
- AWAP data uses the precipitation datasets produced by the Bureau.
- AWAP is available up until the present day.

Disadvantages

- There are several spatial gaps in the AWAP output grids, particularly in South Australia. The gaps occur because lakes, salt lakes and salt pans are features that are not modelled by WaterDyn. These features are not specified in the soil parameter data. Having these gaps, particularly over the lakes, will make it difficult to estimate evaporation from open waterbodies in the water balances.
- The water inputs in any given grid cell are confined to precipitation alone and do not include water added through irrigation, lateral flow or groundwater interaction.

Uncertainty

In a sensitivity analysis undertaken by Raupach et al. (2008), it was found that the most sensitive parameters in the model are:

- the Priestly-Taylor coefficient, albedo and emissivity, which together influence the available energy and potential evaporation
- FAPAR, which influences both energy-limited and water-limited transpiration.

The two most sensitive parameters both influence evapotranspiration outputs. Furthermore, a series of tests were run on the model using independent and subset datasets. The long-term tests found that the main systematic departure of predictions from observations was a tendency for the model to overpredict measured outflows from dry (low-flow) catchments.

The monthly outflow predictions are better than the daily results. Overprediction was found in some catchments, whereas underprediction was more common in others. In some cases baseflow prediction was good, but daily events were not captured.

B.5.3 Murray-Darling Basin Sustainable Yields

Actual evapotranspiration (AET)

AET was estimated in the MDBSY project by using a combination of two methods (Guerschman et al., 2008).

The first method uses surface temperature remotely sensed by the Advanced Very High Resolution Radiometer (AVHRR) series of satellite instruments for the period 1990–2006 and combines this with spatially interpolated climate variables to estimate AET from the surface energy balance (McVicar et al., 2008).

The second method loosely follows the FAO56 ‘crop factor’ approach and scales interpolated potential evaporation estimates using observations of surface greenness and wetness made by the MODIS satellite instrument. This method is constrained by using direct on-ground AET measurements at seven study sites (Guerschman et al., 2009)

The AVHRR method

The AVHRR method uses remotely sensed data and standard meteorological data to generate a Normalised Difference Temperature Index (NDTI). This index is combined with a PET surface to provide an estimate of AET (in mm day^{-1}). The gridded 1-km datasets generated have been shown to provide an accurate estimate of actual evaporation from large waterbodies (Guerschman et al., 2008).

The MODIS method

This dataset was derived by using an algorithm developed to estimate monthly AET on the basis of surface reflectance and interpolated climate data. The algorithm uses monthly values of the Enhanced Vegetation Index (EVI) and the Global Vegetation Moisture Index (GVMI) derived from the MODIS-Terra data to calculate vegetation greenness and moisture availability in the canopy and at the surface. It combines these indexes with gridded monthly estimates of Priestly-Taylor reference ET and precipitation (Guerschman

et al., 2009). The AET calculated includes evaporation from soil and surface water, plant transpiration, and evaporation from intercepted precipitation.

The model is based on a reference ET scaling method and is therefore largely empirical.

An advantage of this method is, however, that it is independent of land cover type, and therefore the model calibration is the same for all land cover types. This method is calibrated by using flux tower measurements, but it is not physically limited by water balance calculations. It does not assume that precipitation is the only input to each gird cell and thus does allow for the input of water from irrigation, lateral flow and groundwater interaction.

CSIRO produced this data specifically for the pilots, but a very similar method was used in the Murray Darling Basin Sustainable Yields Project (Guerschman et al., 2008). The data are available on a 500-m-grid spatial resolution and monthly time-step from February 2000 to June 2009. This dataset would need to be extended for use in the Australia Water Resource Assessment 2010 or the 2010 National Water Accounts.

The 'merged' AET dataset

Both methods were compared with the AET measurements at seven study sites and with catchment streamflow observations from more than 200 catchments across Australia. As the direct AET data were used in the definition of the MODIS dataset there was greater agreement between the site data and the MODIS versus the AVHRR. However, the MODIS-based method also showed a better agreement with the AET estimates from the 220 unimpaired catchments in south-east Australia. Because of the better agreement, the AVHRR AET estimates were modified to match the MODIS AET estimates and a 'merged' AET estimation was generated. This allows the two different methods to be used during different times and still be consistent. The merged AET estimates use data from the AVHRR approach from 1990 to 1999 and from the MODIS method for 2000 to 2006. Both methods provide AET estimates at 1-km resolution (Guerschman et al., 2008).

Land cover

A land cover map was required to isolate areas of specific interest, wetlands, rivers and irrigation areas, as well as for feeding into the AVHRR method. A land cover map of irrigated areas, floodplains and drylands was generated from maps from the Bureau of Rural Sciences, hydrographic maps from Geosciences Australia, and a wetland map from the NSW Department of Environment and Climate Change (Guerschman et al., 2008).

B.5.4 Water2010

Water2010 consists of two modelling approaches based on annual and monthly water balances. The main difference between the two approaches is the assumptions made around soil water storage. In the steady-state water balance model on the annual time scale, it was assumed that changes in soil water storage are negligible over the long term. On the monthly time scale the model is adjusted such that evapotranspiration is a function of rainfall, potential evapotranspiration and change in soil water storage.

Average annual steady-state water balance model

The steady-state catchment water balance model states that precipitation is equal to total evaporation (soil evaporation and transpiration) plus runoff (as surface/sub-surface runoff) and drainage to below the root zone (Welsh et al., 2007).

Actual Evapotranspiration (AET) is put into the average annual steady-state catchment water balance model developed at BRS; this model requires gridded inputs of land cover, precipitation, AET and soils.

Potential evapotranspiration (PET)

- Potential evaporation (PE) is sourced from CSIRO.
- National mean monthly PE grids using the Priestley-Taylor method are applied to data from the period 1980–1999 for use in the BiosEquil model. The rationale for this was that when a sufficiently large region is well supplied with water the total evaporation is determined only by the available radiant energy and is equal to the Priestly-Taylor evaporation rate.
- These grids therefore provide an estimate of PET from a large irrigated area under no water shortage.
- The grid resolution is 0.05° (~5 km).

Actual evapotranspiration (AET)

AET is calculated in the steady-state model by using the following equation:

$$E = \left(1 + \frac{E_0}{P} - \left(1 + \left(\frac{E_0}{P} \right)^{\alpha} \right)^{\frac{1}{\alpha}} \right) P$$

E = evapotranspiration

E_0 = potential evapotranspiration

P = rainfall

α = plant-available water coefficient.

- Evaporation is determined by water supply (rainfall) in dry environments and energy supply (radiation) in wet environments.
- A single-parameter hyperbolic function interpolates between dry (rainfall-limited) and wet (energy-limited) total evaporation rates.
- The purpose of the α parameter is to describe the influence of catchment land characteristics on AET. Annual values of α were estimated for the different land-use classes on the basis of the findings of Zhang *et al*. (2004) and other considerations such as relative leaf area and rooting depth.
- Gridded national land-use data were categorised into 15 classes for use in the catchment water balance model.

Irrigated areas

- Evapotranspiration for grid cells that are irrigated is said to be equal to potential evapotranspiration for the cells.
- In irrigated areas it is assumed that there is no surface runoff over and above that generated from precipitation, and vegetation growth is limited only by energy.
- For the annual steady-state water balance model, it was assumed that changes in soil water storage were negligible at an annual time scale.

Monthly steady-state water balance model

- In order to estimate steady-state monthly water balances, the model was adjusted such that evapotranspiration is a function of rainfall, potential evapotranspiration and change in soil water storage.

$$E = \left(1 + \frac{E_0 + \Delta S}{P} - \left(1 + \left(\frac{E_0 + \Delta S}{P} \right)^{\alpha} \right)^{\frac{1}{\alpha}} \right) P$$

E = evapotranspiration

E_0 = potential evapotranspiration

P = rainfall

ΔS = change in water storage

α = plant-available water coefficient.

- Introducing change in soil water storage into the model required monthly estimates of soil water to be generated.
- Long-term, monthly relative soil moisture indexes were sourced from CSIRO (Raupach, 2001).
- Soil moisture was estimated by multiplying these indexes by water-holding-capacity data sourced from the NLWRA from observations by CSIRO and State soil agencies (ASRIS).

Additional changes to the annual model include:

- Whereas dryland cropping continued to be classified as summer or winter during land-use analyses, crop areas that fell under irrigation grid cells were simply delineated as ‘irrigated cropping’ rather than ‘irrigated summer crop’ or ‘irrigated winter crop’.

Appendix C Rainfall–runoff model types

Table 9. Rainfall–runoff model types

Model type	Description (from Viney (2008))
Lumped model	Lumped models are designed to be applied at the catchment scale without any further spatial subdivision. Input data (precipitation and potential evaporation) are averaged over the catchment or extracted from single-site observations within or near the catchment, and predictions of streamflow are available only at the catchment outlet. Most lumped models are conceptual, in that their model equations are designed to represent conceptually, but not necessarily physically, the main hydrological processes. In general, these models require calibration of their parameters against observations of streamflow at the catchment outlet.
Spatialised lumped model	Spatialised lumped models is the term that has been applied to lumped rainfall–runoff models that are applied at the scale of gridded input data, such as the approach used in the Murray Darling Basin Sustainable Yields Project. The gridded input data include daily precipitation and potential evaporation data. All cells within a catchment use the same parameter set, calibrated by comparison of the accumulated predictions against the observed streamflow. Since each cell within a catchment has unique precipitation and potential evaporation input, the resulting runoff predictions are spatially distributed within the catchment. This results in a modelling approach that is intermediate between the lumped methods and the semi-distributed methods.
Semi-distributed model	Semi-distributed modelling represents a step up in complexity in comparison to the lumped approaches. In general, semi-distributed models retain some characteristics of the lumped models – particularly their conceptualised bucket approach. Semi-distributed models are characterised by: • discretisation of a catchment into a number of subcatchments on the basis of factors such as the channel network, gauging locations, land-use patterns, soil patterns or elevation bands • the possibility of incorporating information from gauged subcatchments within a catchment for use in model calibration • a routing scheme.
Fully distributed model	Distributed modelling is often synonymously known as physically based modelling. It resolves the landscape down to units the size of a DEM grid cell (typically tens of metres). Within each cell, flux equations are used to direct water flows both laterally from cell to cell and vertically through a number of soil layers. These equations are usually based on the known physics of soil-water interactions. Their physical basis places great demands on input data – especially the requirement for spatially and vertically explicit, high-density soil characteristics – and on computational resources.

C.1 Rainfall–runoff models

A number of water balance models have been described in the literature and are listed in Table 10 below, together with a description of the applicability of each model for the purposes of developing a national water balance.

Table 10. Rainfall–runoff models

Model type	Comments on applicability
Lumped models	
1. Stanford Watershed Model	The Stanford Watershed model was used in the USA and UK and was tested and found to perform as well as several others in Australia and 'performed better than Sacramento, but Sacramento was adopted in Australia after the Bureau considered it in its flood forecasting research.' (Tom McMahon, pers. comm.)
2. Sacramento	Widely used in Australia and internationally, but the model has 17 parameters, which tends to result in better results for directly calibrated catchments than other models with fewer parameters. Recently employed in the various Sustainable Yields projects and elsewhere (Viney et al., 2009a).
3. Sixpar model	This is a submodel of the Sacramento model (the percolation component only) and therefore does not provide the runoff values required for the water balance.
4. WATBAL	A simple bucket model run at a weekly or monthly time scale used in conjunction with crop growth models; its ability to produce runoff is limited.
5. SWAT (Soil & Water Assessment Tool)	Widely used internationally. It can handle the effects of land use and climate change on the water balance and on water quality. SWAT is used in the USA to assess water resources but is a complex model.
6. SMAR (Soil Moisture Accounting and Routing)	A quasi-physical conceptual rainfall runoff model. Recently employed in the various Sustainable Yields projects and elsewhere (Viney et al., 2009a).
7. IHACRES	This is a time series model rather than a conceptual model; therefore it does not describe the catchment processes that generate runoff. Recently employed in the various Sustainable Yields projects and elsewhere (Viney et al., 2009a). It is noted that this model shows a lower degree of bias than others considered in that study.
8. PDM	Widely used in the UK but has not been applied to Australian catchments; therefore, the performance is unknown.
9. Xinanjiang	This model is similar to PDM and used predominantly in China. The model has been applied in Australia (Zhang and Chiew, 2009), in a paper testing regionalisation methods that also incorporate leaf area index data.
10. Tank Model	A simple structured model widely used in Japan. This model has not been tested on Australian catchments.
11. NAM	Used in many parts of the world but is reasonably complex (13 parameters) and there is a lack of the expertise necessary to apply the model widely in Australia.
12. Australian Representative Basin Model (ARBM)	Developed by the CSIRO in the 1960s but not widely used because the model requires 6-minute rainfall data during rain events.
13. Boughton's Model	This model has been superseded by the AWBM.
14. SFB Model	This is a simplified (three-parameter) version of Boughton's Model and has been superseded by the AWBM.
15. Australian Water Balance Model (AWBM)	Widely used in Australia, but includes three surface stores, which makes it harder to obtain soil moisture. It is difficult to obtain the parameters of the model by an optimising routine, as it is over parameterised.
16. Hydrolog (Monash model)	This model incorporates a catchment water balance procedure as well

Model type	Comments on applicability
	as a routing procedure, but it has 17 parameters and has since been modified and re-released as Modhydrolog.
17. Modhydrolog (Modified Hydrolog)	This model is a version of Hydrolog modified to include a groundwater component and has 19 parameters; it may be too complex to apply.
18. Simhyd (Simplified Modhydrolog)	This is a version of Modhydrolog simplified by fixing a number of parameters, resulting in a total of seven. This model has been applied widely in Australia.
Semi-distributed models	
1. HBV	Developed in Sweden and used in over 30 countries. Requires 12 parameters for each subcatchment and may be difficult to apply.
2. LASCAM	Developed as part of a higher degree study and has not been used widely.
3. MAGIC	A steady-state model developed for modelling salinity within Western Australia. Has been applied there in several studies.
4. LUCICAT	A dynamic model developed recently as part of a higher degree study, primarily for modelling salinity within Western Australia. The model has been used in a few catchments in Western Australia, including within the recent South West Western Australia Sustainable Yields Project. Is also being trialled elsewhere in the Bureau at the Thomson catchment (near Melbourne) for extended hydrological prediction use.
Distributed models	
1. Thales	This is a detailed event model developed for very small catchments; it does not include evapotranspiration in the water balance.
2. Topog	Developed as an event model and uses the stream tube concept. This model has not been applied to large catchments.
3. WEC-C	This model has been used in a few catchments in Western Australia
4. SIMPLE	This model was developed to run using radar data.
5. TOPMODEL	TOPMODEL has been applied in New Zealand to forecast streamflow. This is a grid-based model but does not represent hydrological processes as well as TOPKAPI does.
6. SHE	Application of the SHE model requires large amounts of parametric and input data, some of which, like crop parameters, may be time dependent. Considerable computing resources are required to handle large arrays and to perform iterative solutions.
7. TOPKAPI	This model can be applied using public domain data and has been used in South Africa to obtain near real time soil moisture. TOPKAPI has been used widely in Europe and in China.
8. CLASS	May be used for seasonal water availability forecasting within the Bureau of Meteorology in the future and should therefore be considered for consistency.
9. SAFRAN/ISBA/MODCOU	This is a complete model consisting of a meteorological analysis system (SAFRAN), a land surface model (ISBA) and a hydrogeological model (MODCOU). The model has been applied in France to the whole country but is beyond the scope of the Bureau.
10. WaterDyn	The model has already been applied to the whole of Australia and is available for immediate application.
11. CABLE	CABLE is the land surface module for the climate and Earth system model ACCESS being developed by the CSIRO and the Australian Bureau of Meteorology. Currently the hydrological processes are represented too simplistically, and comparison with observed streamflow shows a positive bias in the modelled runoff.
12. MIKE SHE	The DHI Integrated Groundwater/Surface Water modelling framework. The DHI implementation of SHE, including subsequent extensions. Usually applied at the catchment scale because of data/computational requirements.

The Standford Watershed Model was the first digital computer water balance model; it was developed at the Standford University in 1964. It was not widely used and was later superseded by the Sacramento model. Sixpar is a simplified version (Gupta and Sorooshian, 1983; Gupta and Sorooshian, 1985) of the Sacramento soil moisture accounting model. WATBAL (Keig and McAlpine, 1974) is a simple bucket model developed at the Division of Land Research, CSIRO and run at a weekly and monthly time scales. It was used mainly in conjunction with crop growth models such as GROWEST, and its ability to produce runoff is limited.

The Boughton model was the first computer simulation model of catchment water balance developed in Australia (Boughton, 1968). It was developed with agricultural-scale catchments as the main application and did not contain a baseflow runoff component. The baseflow component was added in later versions of the model. The SFB model was developed from the Boughton model, with many of the original non-sensitive parameters given fixed values (Boughton, 1984). The letters in the name refer to the three parameters in the model: S for the surface storage parameter, F for the percolation parameter, and B for the baseflow discharge parameter. The model was extensively used because of the small number of parameters and its overall simplicity. The SFB was eventually replaced in terms of usage within Australia, mainly by the use of AWBM, and is consequently little used now.

The Hydrolog (Monash) Model was developed at Monash University (Porter and McMahon, 1971; Porter, 1972). The model contains a catchment water balance procedure and a runoff routing procedure, similar to the RORB flood hydrograph model. It can be operated on either a daily or hourly time-step and has 17 parameters. The baseflow processes in HYDROLOG were modified to produce the MODHYDROLOG model (Chiew, 1990; Chiew and McMahon, 1990, 1991). This model has 19 parameters. A sensitivity analysis by Chiew and McMahon (1993) showed that modelled streamflow was insensitive to many of the parameters, and a simplified version with seven parameters, SIMHYD, was developed (Chiew et al., 2002).

The Xinanjiang (Zhao, 1992) model is similar to the PDM model and is not discussed here. The IHACRES model was jointly developed by the UK Institute of Hydrology and the Centre for Resource and Environmental Studies at the Australian National University (Jakeman et al., 1990). The model operates on a daily time-step and calculates quick flow and slow flow (i.e. surface runoff and baseflow) components of streamflow. The original version used a statistical approach to determine the runoff. Evans and Jakeman (1998) introduced a moisture-accounting procedure (i.e. a change to a water balance model) to determine losses from rainfall and the generation of runoff [see also Croke and Jakeman (2004)]. The model inputs temperature data in lieu of ET estimates and outputs calculated ET values as well as calculated runoff.

The tank model is a lumped model (Sugawara et al., 1974; Sugawara, 1979) having a simple structure and is widely used in Japan. It consists of a number of tanks stacked on top of another.

The SIMPLE model is a process-based hydrological model to simulate the hydrological budget of a catchment (Kouwen, 1988). Because the model is aimed at flood forecasting using radar rainfall data, only the most dominant hydrological processes affecting flood flows are included. There are interception, surface storage, infiltration, interflow, overland flow and baseflow. The rainfall, streamflow and catchment data are stored and processed in a square grid coordinate system. The total inflow to the river system is found by adding the surface runoff from both the pervious and impervious areas, as well as the interflow and the baseflow. A storage routing technique is used to route the water through the channel system.

Thales is a simple distributed model (Grayson et al., 1992a, 1992b) that incorporates both the Hortonian surface runoff as well as saturation excess runoff and exfiltration of subsurface flow. Evaporation is not represented, since the purpose of the model is to

simulate individual events. The model was applied to two small experimental catchments with disappointing results. However, it is noted that the model was formulated as a research tool 'to explore some of the detailed hydrologic process as short time intervals $\Delta T \sim 1$ minute' (Tom McMahon, pers. comm.), and any judgment of the model's performance should consider this context.

The TOPOG is a contour-based model (O'Loughlin et al., 1989) developed at the Australian Centre for Catchment Hydrology for use on hillslope catchments. A hillslope catchment is divided into a number of elements by a set of contour and flow lines. All the elements between a pair of flow lines constitute a flow strip. The saturated flow depth in each element depends on the local slope, transmissivity, upstream contributing flow, rainfall on the element and evaporation from the element.

Water and Environmental Consultants – Catchment (WEC-C) is a distributed, deterministic catchment model for the simulation of water and solute fluxes in a landscape. The model framework is a rectangular grid of uniform cell size combined with a system of soil layers, of variable thickness, in the vertical direction. All parameters are defined locally in each computational cell so that all available data on catchment variability can be incorporated directly into the model. The model has been described by Croton and Barry (2001) and has been successfully applied to different land uses in the south-west of Western Australia (e.g. Bari and Croton, 2000; Croton and Barry, 2001).

The following models are briefly described and evaluated for their suitability for water resources assessment of Australia:

1. Sacramento
2. AWBM
3. SIMHYD
4. PDM
5. NAM
6. SWAT
7. HBV
8. LASCAM
9. MAGIC
10. LUCICAT
11. TOPMODEL
12. SHE
13. WaterDyn
14. CLASS
15. CABLE
16. TOPKAPI
17. SAFRAN/ISBA/MODCOU
18. MIKE SHE

C.1.1 Model 1: Sacramento Soil Moisture Accounting model (SAC-SMA)

The following description of the model is taken from the User Guide for the Rainfall Runoff library (RRL; user guide available at toolkit.ewater.com.au/rrl). The Sacramento model is a conceptual catchment water balance model developed for the U.S. National Weather Service that models the rainfall–runoff process at daily, 6-hourly or 1-hourly time-steps (Figure 11) (Burnash et al., 1973).

Currently, the version of the Sacramento model available in RRL operates with daily data and a daily time-step. The model contains five stores. There are two surface stores with surface evaporation, surface runoff and interflow. The three baseflow stores are used to represent soil evaporation and two stages of baseflow. The original version of the Sacramento model has 16 parameters that can be estimated from soil moisture observations and soil type data; however, in most cases five to seven parameters can be replaced with constants without any loss of quality (Kuzmin et al., 2008). The model is available in lumped and distributed modes. However, its distributed version is potentially difficult to calibrate and, as a result, it does not necessarily provide better forecasts than the lumped version (Reed et al., 2004). Because of its reliability Sacramento has been widely used operationally by the U.S. National Weather Service and in Australia (Boughton, 2005).

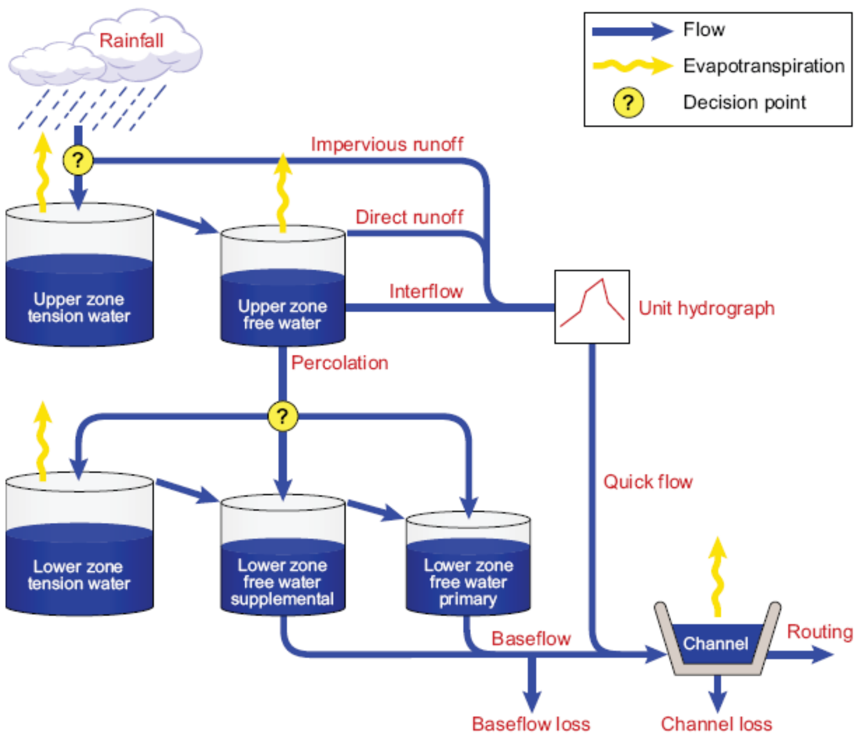

Figure 11. Structure of the Sacramento Model

C.1.2 Model 2: Australian Water Balance Model (AWBM)

The following description of the AWBM model is taken from the RRL User Guide (see Figure 12). The AWBM is a catchment water balance model that can relate runoff to rainfall with daily or hourly data, and it calculates losses from rainfall for flood hydrograph modelling. Note, however, that the RRL is currently geared towards modelling at a daily time-step and AWBM is not run on hourly data. AWBM requires evapotranspiration as an input, whereas most models will take PET as input.

The model uses three surface stores to simulate partial areas of runoff. The water balance of each surface store is calculated independently of the others. The model calculates the moisture balance of each partial area at either daily or hourly time-steps. At each time-step, rainfall is added to each of the three surface moisture stores and evapotranspiration is subtracted from each store. The water balance equation is:

$$store_n = store_n + rain - evap \qquad (n = 1 \text{ to } 3) \qquad (1)$$

If the value of moisture in the store becomes negative, it is reset to zero, as the evapotranspiration demand is superior to the available moisture. If the value of moisture in the store exceeds the capacity of the store, the moisture in excess of the capacity becomes runoff and the store is reset to the capacity.

The three parameters, A1, A2 and A3, representing the proportions of the areas of the catchment are constrained; thus only A1 and A2 can be set. The default pattern is A1= 0.134, A2= 0.433, A3= 0. 433, and this pattern is fixed (i.e. calibration tools will not modify it). When A1 and/or A2 are changed, A3 will be adjusted to respect the constraint. If the user increases A1, and A3 cannot compensate; A1 is then reduced to still respect the constraint.

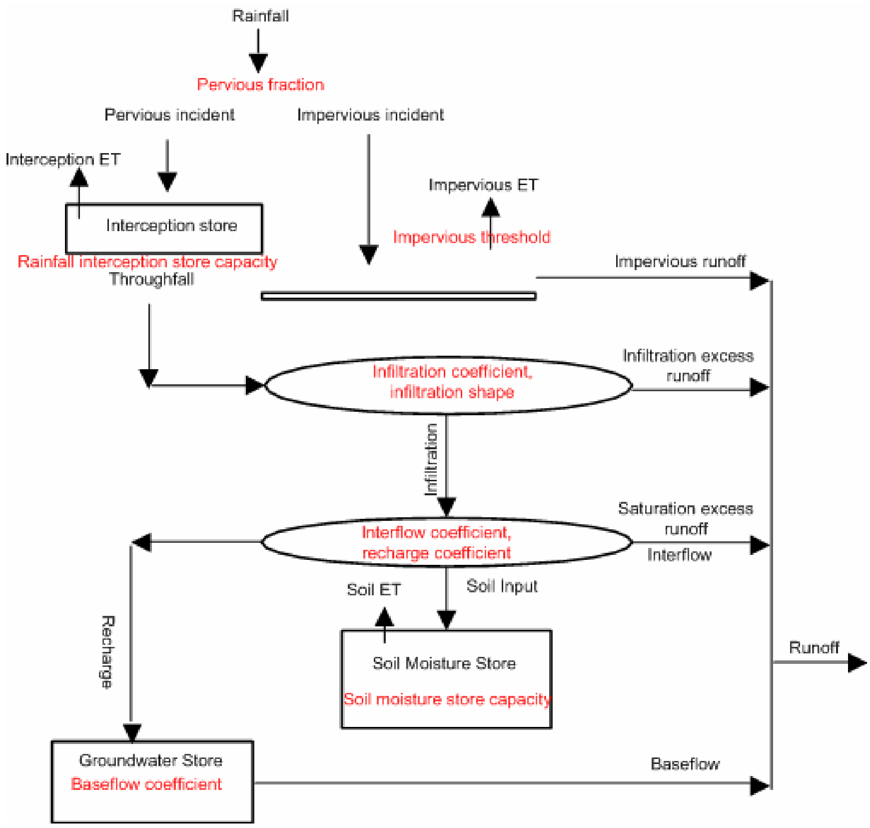

Figure 12. Structure of the AWBM rainfall–runoff model (from RRL User Guide)

When runoff occurs from any store, part of the runoff becomes recharge of the baseflow store if there is baseflow in the streamflow. The fraction of the runoff used to recharge the baseflow store is BFI*runoff, where BFI is the baseflow index, i.e. the ratio of baseflow to total flow in the streamflow. The remainder of the runoff, i.e. (1.0 – BFI)*runoff, is surface runoff. The baseflow store is depleted at the rate of (1.0 – K)*BS, where BS is the current moisture in the baseflow store and K is the baseflow recession constant of the time-step being used (daily or hourly).

The surface runoff can be routed through a store if required to simulate the delay of surface runoff reaching the outlet of a medium to large catchment. The surface store acts in the same way as the baseflow store and is depleted at the rate of (1.0 – KS)*SS, where SS is the current moisture in the surface runoff store and KS is the surface runoff recession constant of the time-step being used.

C.1.3 Model 3: SIMHYD

The following description of the SIMHYD model is taken from the RRL User Guide. SIMHYD is a daily conceptual rainfall–runoff model that estimates daily streamflow from daily rainfall and areal potential evapotranspiration data. The structure of the simple lumped conceptual daily rainfall–runoff model, SIMHYD, is shown in Figure 13. In SIMHYD, daily rainfall first fills the interception store, which is emptied each day by evaporation. The excess rainfall is then subjected to an infiltration function that determines the infiltration capacity. The excess rainfall that exceeds the infiltration capacity becomes infiltration excess runoff.

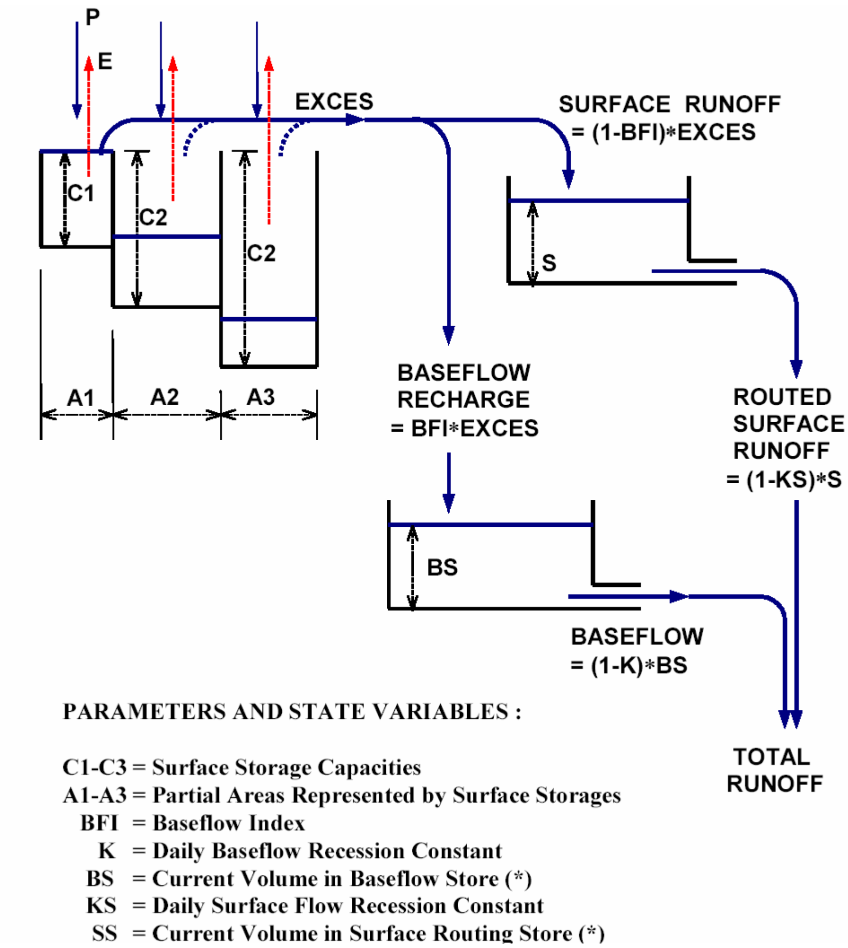

Figure 13. Structure of the SIMHYD rainfall–runoff model (from RRL User Guide)

C.1.4 Model 4: Probability Distributed Moisture (PDM) Model

The Probability Distributed Moisture (PDM) model is a conceptual rainfall–runoff model that transforms rainfall and evaporation data to flow at the catchment outlet (Moore, 1985; Moore and Bell, 1999). Figure 14 shows the general form of the model.

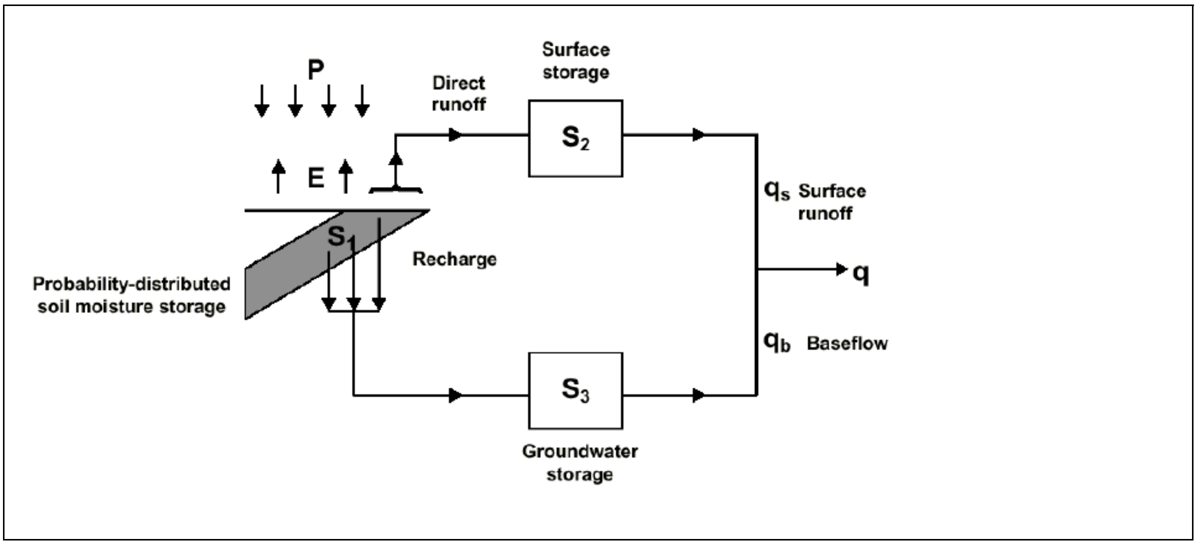

Figure 14. Structure of the PDM rainfall–runoff model

The runoff production at a point in the catchment is controlled by the absorption capacity of canopy interception, surface detention and soil water storage processes. The spatial variation of the soil water storage capacity is modelled by a probability distribution. The standard form of the PDM model uses a truncated Pareto distribution of store capacities.

Drainage from the probability-distributed moisture store S_1 enters the groundwater storage as recharge. The rate of drainage expressed as a depth over the basin per unit time is a function of the water in store in excess of a tension storage threshold S_t.

The direct runoff generated from the saturated probability-distributed stores is routed to the basin outlet through a quick response system. This is represented by a cascade of two linear reservoirs. Baseflow is obtained by using the nonlinear relationship, and the total flow is the sum of surface runoff from the linear reservoirs and baseflow.

The PDM model has 10 parameters.

C.1.5 Model 5: NAM model

The NAM model is a conceptual representation of the land phase of the hydrologic cycle. It simulates the rainfall–runoff process occurring at the catchment scale. Precipitation, potential evapotranspiration, temperature and radiation time series if snow accumulation and melt are to be modelled are the basic data requirements of the model. The model produces a time series of catchment runoff, subsurface flow contributions to the channel, and information about the other elements of the land phase of the hydrologic cycle, such as moisture content and groundwater recharge.

The rainfall–runoff process is simulated by continuously accounting for the water content in four different and mutually interrelated storages (snow storage, surface storage, lower or root zone storage and groundwater storage) representing different physical elements of the catchment. The model has the following 13 parameters:

Umax – maximum water content in surface storage

Lmax – maximum water content in root zone storage

CQOF – overland flow runoff coefficient

CKIF – time constant for inter-flow

CK1_2 – time constant for routing overland flow

TOF – root zone threshold value for overland flow

TIF – root zone threshold value for inter-flow

CKBF – time constant for routing baseflow

Tg – root zone threshold value for groundwater recharge

Cqflow – lower baseflow. Recharge to lower reservoir

Cklow – time constant for routing lower baseflow

Csnow – constant degree-day coefficient

T0 – base temperature snow/rain

The structure of the NAM model is shown in Figure 15.

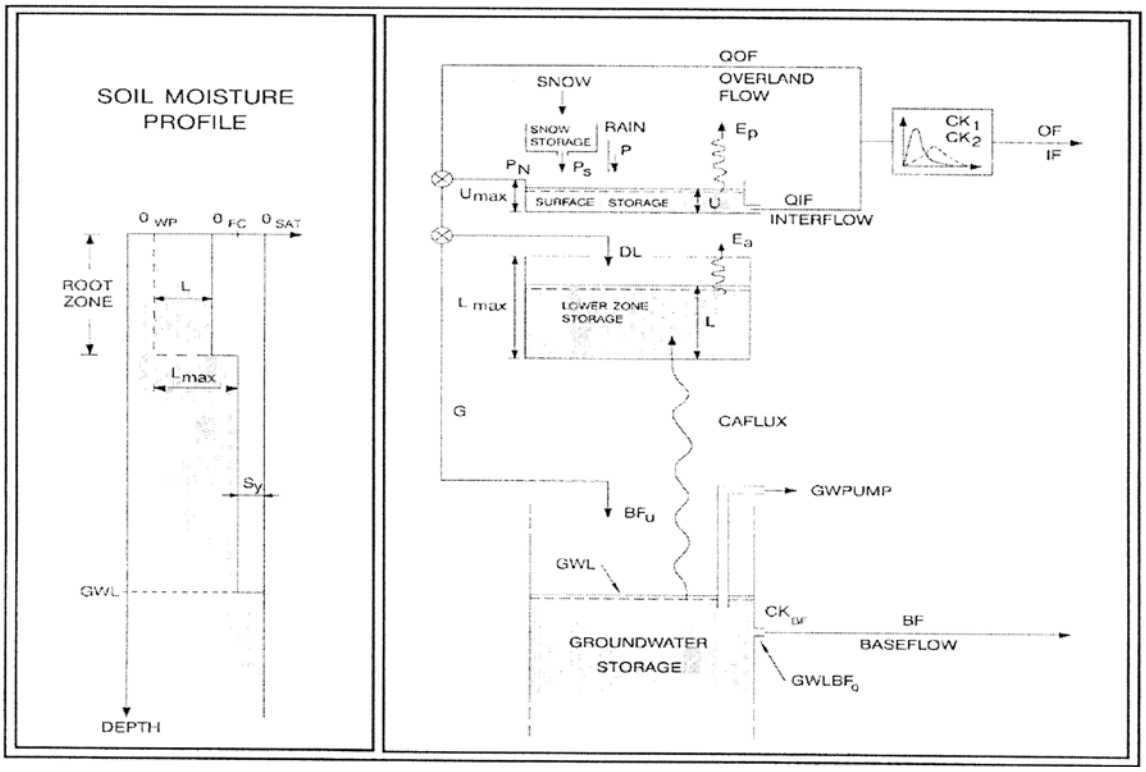

Figure 15. Structure of the NAM rainfall–runoff model

C.1.6 Model 6: Soil & Water Assessment Tool (SWAT)

SWAT was developed by the United States Department of Agriculture for use in the United States but has since become prominently used worldwide for studies investigating the impacts of land use and climate change on the water balance and water quality (erosion, nutrients and pesticides) of agricultural catchments. A large body of literature exists detailing the numerous applications of SWAT. A complete description of the model can be found in the work of Neitsch et al. (2001). For the benefit of the readers a brief description of SWAT is presented here.

SWAT (Figure 16) is a physically based, distributed hydrologic model. SWAT operates on a daily time-step and has the capabilities to continuously simulate 100 years of streamflows. SWAT is also a non-point-source pollution model that simulates the transport of sediment, nutrients and pesticides through catchments. SWAT is a comprehensive tool that enables the impacts of land management practices on water, sediment and agricultural chemical yields to be predicted over long periods of time for large complex watersheds that have varying soils and land-use and management practices (Neitsch et al., 2001). Specific information for climate, soils, topography, and land use is required to run the model. The main algorithms used in modelling the processes of the hydrologic cycle are presented in Table 11.

Table 11. Summary of algorithms used by SWAT (Neitsch et al., 2001)

Hydrologic process	Algorithms
Surface runoff	SCS Curve Number method; Green & Ampt Infiltration method
Channel routing	Variable storage routing method; Muskingum routing method
Percolation	Storage routing method
Interflow	Kinematic storage model
Groundwater	Baseflow recession constant; groundwater storage; re-evaporation
Evapotranspiration	Penman-Monteith; Hargreaves; Priestley-Taylor

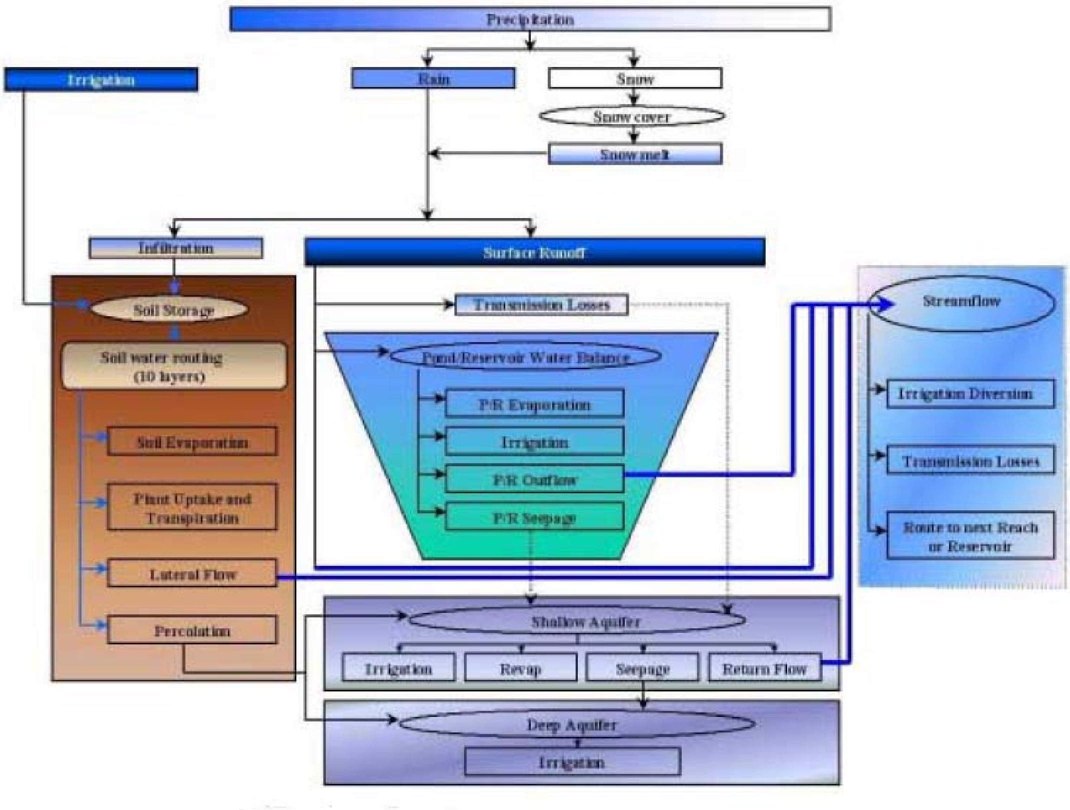

Figure 16. Structure of SWAT (SWAT User Manual Version 98.1)

Model operation:

- daily time-step with long-term simulations
- basins subdivided to account for differences in soils, land use, crops, topography, weather, etc.
- basins of several thousand square kilometres can be studied
- soil profile can be divided into 10 layers
- basin subdivided into subbasins or grid cells
- a reach routing command language is used to route and add flows
- hundreds of cells/subbasins can be simulated in spatially displayed outputs
- groundwater flow model
- SWAT accepts output from EPIC
- SWAT accepts measured data and point sources
- water can be transferred from channels and reservoirs
- nutrients and pesticide input/output
- Windows interface
- GRASS GIS links to automate inputs.

C.1.7 Model 7: HBV Model

The HBV model (Bergström, 1976, 1992), developed at the Swedish Meteorological and Hydrological Institute (SMHI), has been shown to give a good estimate of runoff from several Scandinavian catchments (Lundberg, 1982). It uses sub-catchments as primary hydrological units, and within these an area-elevation distribution and a crude classification of land use are made (Figure 17).

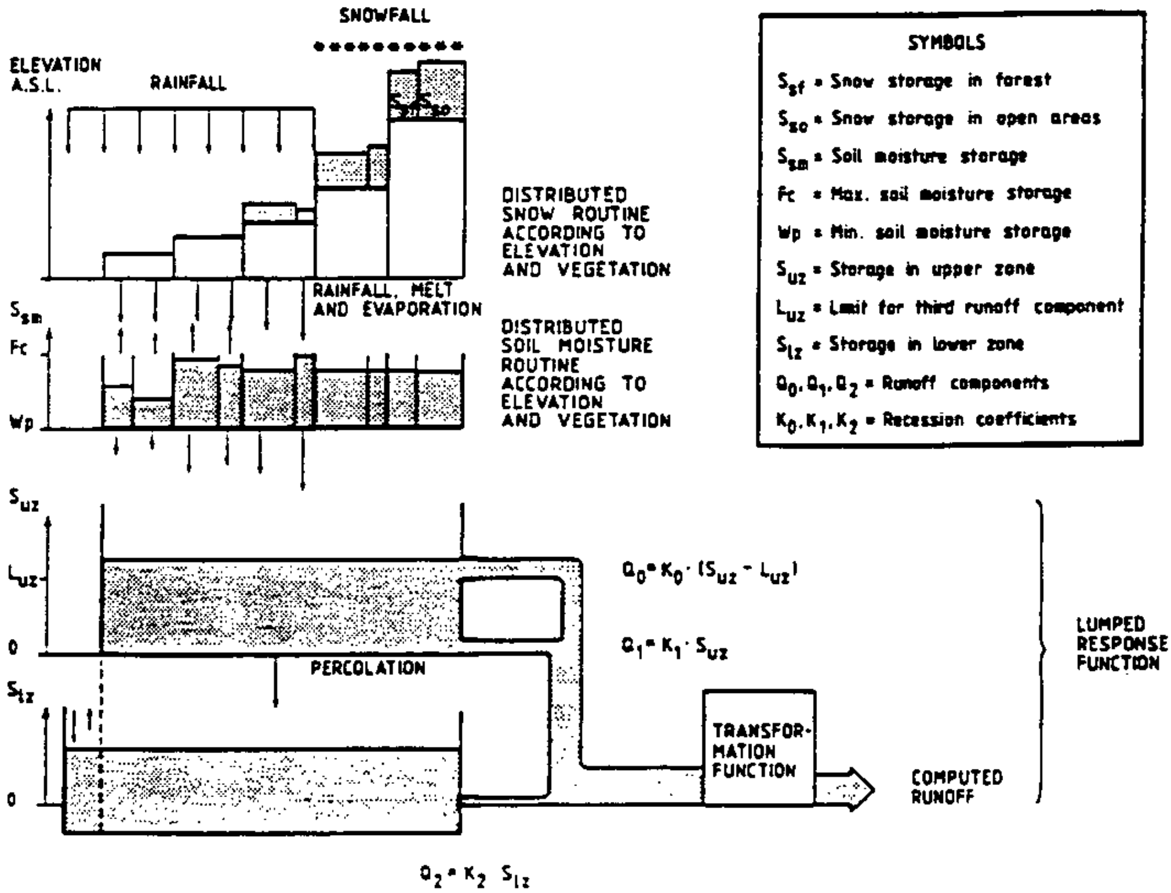

Figure 17. Structure of the SMHI version of the HBV model when applied to one sub-catchment (Bergström, 1992)

The model has a number of free parameters that are found by calibration. For a sub-catchment with only one type of vegetation, the model has 12 parameters. The model has been applied in more than 30 countries worldwide.

C.1.8 Model 8: LASCAM

The LArge Scale CAtchment Model (LASCAM) was developed through the Centre for Water Research (CWR) for the purposes of water and salt balance modelling. It uses gridded topographic information to define a stream network and to disaggregate the catchment into a series of interconnected subcatchments of area 1 to 5 km^2. The subcatchments are the basic building blocks of the model. The hydrological processes are modelled at this scale before being aggregated to yield the response of the entire catchment.

LASCAM is constructed around four conceptual soil stores, the A Store, the D Store, the B Store and the F Store (Zammit et al., 2002). Figure 18 represents the hillslope with these stores that form the basic subcatchment hydrology. The stores are typical representations of accumulations of soil water in duplex soil profiles.

The A Store represents the perched, near-stream aquifer. Streamflow is generated for this store by the mechanisms of infiltration excess runoff, saturation excess runoff and baseflow. Infiltration excess and Saturation excess runoff are governed largely by the level of the A Store. A small amount of recharge into the stream zone occurs through baseflow (Zammit et al., 2002). Figure 18 illustrates how the pathways of water meet up and intersect. D Store represents the unsaturated topsoil (Zammit et al., 2002). The majority of evaporation and transpiration occur through this store, being the store that most vegetation is located in, although this does extend to the F Store and the B Store, with the presence of deep-rooted vegetation. The D Store recharges the A Store by subsurface flow, known as throughflow. Rainfall that is not intercepted by the vegetation canopy and eventually evaporated is referred to as throughfall. Throughfall is partitioned into that available for infiltration or saturation excess runoff. Infiltrating water percolates through the unsaturated F store, ultimately reaching the permanent B store. The F Store is the intermediate unsaturated zone. Flow from the A Store recharges the F Store, which in turn recharges the B Store (Figure 18). Water does not accumulate in the F Store. The dry salt store, the P Store, is located in the F Store, and is dissolved as water flows through the store to recharge the B Store and as the groundwater level (B Store level) rises.

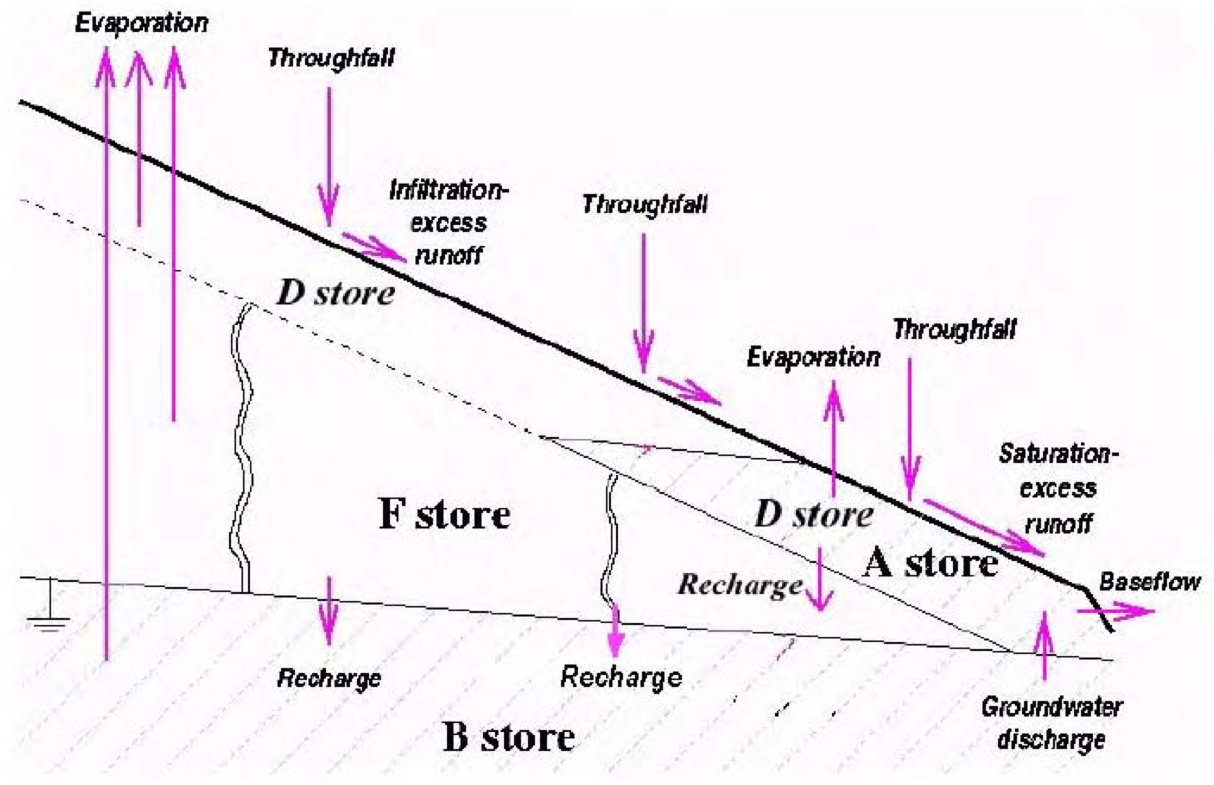

Figure 18. Schematic diagram of a hillslope, showing four conceptual water stores and water fluxes (Zammit et al., 2002)

The water processes are modelled at a subcatchment level on a daily time-step. The water is then aggregated through the stream network to produce a yield response at the catchment outlet. Any water that does not make it to the outlet in 1 day is stored in the system and begins the next day along the subcatchment links. The water is routed throughout the system to produce the final streamflow and streamload predictions at the catchment outlet. For each subcatchment there is a set of physically based equations that define the quantity and distribution of water and salt involved in the subcatchment store processes. The parameters of these equations are not able to be estimated or derived from field observations or data and therefore need optimising through the process of calibration.

C.1.9 Model 9: MAGIC

MAGIC estimates the impacts of possible land-use management options on streamflow and salinity at the catchment scale. The MAGIC system (Mauger, 1996) uses gridded maps to represent the geographic distribution of catchment characteristics and changes in land use. The model then comprises a script in the MAGIC command language that simulates the physical hydrological processes on a grid cell by grid cell and time-step to time-step basis to estimate streamflow and deep groundwater discharge from a record of rainfall.

The ground surface is represented by the digital elevation model (DEM). Slope, aspect, plan curvature and drainage directions are computed from the DEM. In areas where drainage lines are not strongly defined by the topography, the drainage is constrained to follow the mapped streams. Elsewhere the positions of streams are determined from the DEM.

Subcatchments are chosen to isolate areas of special interest for management planning, and otherwise to subdivide the catchment into its main tributaries. Outlets for

subcatchments are positioned on road crossings if possible so that the culverts could assist in flow estimation in future.

The hydrologically active vertical thickness of the catchment is represented in layers. A generally highly permeable surface layer comprises the normal A and B soil horizons; there is a less permeable layer below that, and finally a more permeable layer above bedrock. The thickness and permeability of these layers at every grid cell in the catchment are determined from other mapping. To calculate the saturated thicknesses of soils, a specific yield is assumed for the surface and middle layers (the term 'porosity' has been used in the model command file, but 'specific yield' is a more correct term, being the volume of water that can freely drain from a unit volume of saturated soil). For the surface layer, properties of soil groups are averaged within each soil subsystem or phase that is mapped in soil-landscape mapping (Schoknecht et al., 2004), using the specified percentages of the soil groups within the mapped units.

Trees and pasture are mapped from summer Landsat TM scenes. Leaf area index for trees is estimated from the Landsat scene, whereas pasture LAI follows a seasonal profile that is scaled to a peak value set as a linear function of average annual rainfall. Cells may contain both trees and pasture.

Lakes are primarily defined by the categories 'lake' and 'swamp' in the digitised maps of lakes. When drains are modelled, the thickness of the surface layer is reduced by the depth of the drain in any cell that contained more than 5 m of a hypothetical drainage line.

Gridded maps of average rainfall for each month of the year for the period are obtained from the Bureau. A gridded map of annual pan evaporation is prepared by interpolating the map of isopleths.

The model runs to simulate the hydrologic steady state for the catchment under a specified constant distribution of vegetation. Average monthly rainfall is applied in time-steps of 1 month. In the ideal steady state, the soil moisture content in every cell at the end of the year would equal the cell's soil moisture at the start of the year. To approximate this, the model is started with all soil saturated, and then run for 3 consecutive years with average rainfall. The annual totals made in the third year are reported as the steady state condition of the catchment. Parameters in the model are calibrated so that the totals correspond to appropriate gauging records.

C.1.10 Model 10: LUCICAT

The land-use-change incorporated catchment (LUCICAT) model is a distributed lumped conceptual hydrological model. The model runs in the LUCICAT Live framework (Bari et al., 2009a). The LUCICAT Live framework consists of the following modules: (i) LUCICAT_Geopro, (ii) LUCICAT_Rain, (iii) LUCICAT_Main, (iv) Calibration and (v) Developing management options. Figure 19 is a flow diagram of the modelling system. The core model is written in FORTRAN 95, but the framework for the LUCICAT model was developed in C# using a Microsoft .NET environment. The development was object-orientated and utilises objects from CSIRO's TIME codes for its capability to produce maps and charts for better understanding of the data and the model. It is designed to allow FORTRAN executables to be run separately in a command shell.

The LUCICAT_Main module contains the fundamental 'building-block' water and salt balance model and the streamflow routing component. A large catchment is divided into smaller Response Units to take into account spatial distribution of rainfall, pan evaporation and land use. Each of the Response Units is represented by the 'open-book' approach and a fundamental 'building-block' model is applied (Figure 20). Response Unit attributes of soil depth, groundwater level and change in land use are also incorporated (Bari and Smettem, 2003; Bari, 2005; Bari and Smettem, 2006a, 2006b). Each Response Unit also forms a building block in the model and consists of (i) Dry, Wet and Subsurface

Stores (ii) a saturated Groundwater Store and (iii) a transient Streamzone Store. The physical processes that the building-block model emulates are listed below:

Evapotranspiration comprises three components: interception, transpiration and evaporation from soil. Interception is represented by a canopy store, which is dependent on the Leaf Area Index. The rest of the rainfall reaches the soil surface and either infiltrates or creates runoff. Transpiration is modelled as a function of the Leaf Area Index, the relative root volume in all five stores, the moisture content and the potential energy (pan evaporation). Evaporation takes place from the Dry, Wet and Subsurface Stores and the Streamzone Store (if it exists).

Surface runoff is generated from variably contributing dynamic saturated areas along the streamzone. Where part of the streamzone is saturated by the presence of the permanent groundwater system, additional surface runoff is generated. The near-stream dynamic saturated area is also responsible for the generation of salt flux associated with surface runoff and interflow. The contributing areas vary both spatially and temporally within a Response Unit.

Interflow is the contribution of shallow, intermittent groundwater after rainfall recharge. If the permanent groundwater system does not discharge to the stream, interflow controls the recession limb of the streamflow hydrograph. Interflow is a function of the lateral hydraulic conductivity of the topsoil and the water content of the Wet Store.

Percolation is the amount of vertical water flow between the highly conductive topsoil (Dry and Wet Stores) and the less conductive Subsurface Store. It is controlled by the vertical conductivity, the water content in the Wet Store and the soil moisture deficit in the Subsurface Store. Most of the percolated water is transpired by the deep-rooted trees, and only a small amount of the water reaches the Groundwater Store. Recharge to the Groundwater Store comprises both matrix and preferential flow.

This model has been applied in a series of salinity situation studies over several water-resource-recovery catchments (Collie, Denmark, Kent, Warren and Helena) by the Western Australian Department of Water. See McTaggart et al. (2008) for background.

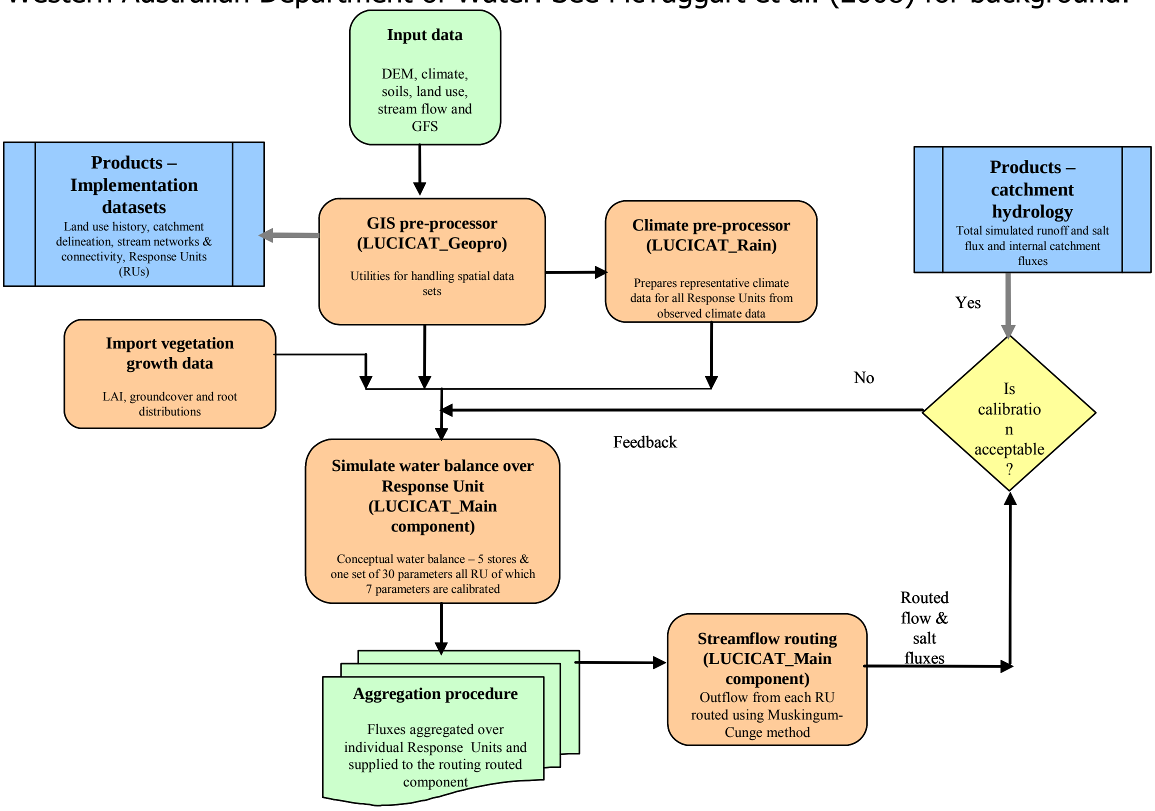

Figure 19. Schematic diagram of LUCICAT Live framework (from Bari et al, 2009a)

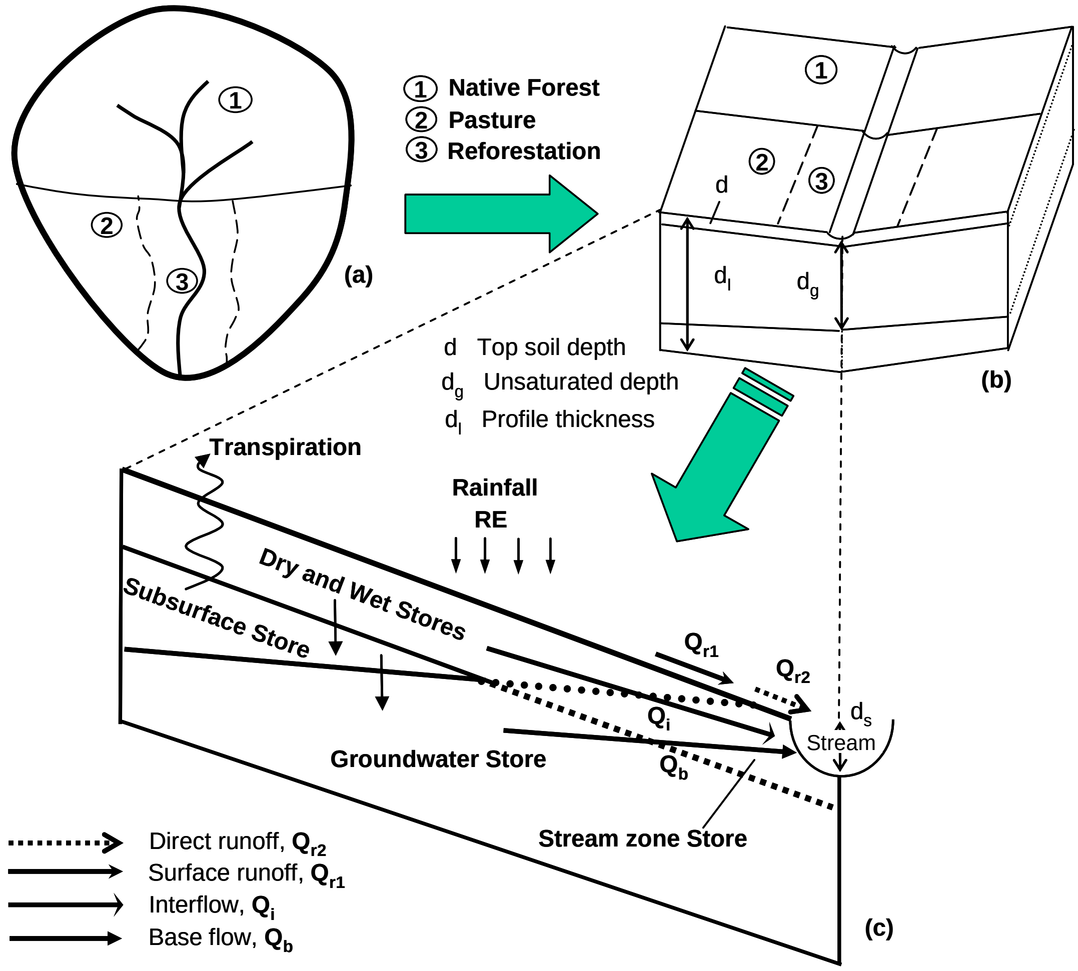

Figure 20. Conceptual diagram of the LUCICAT 'building-block' model (Bari and Smettem, 2006a)

Baseflow is the contribution of the (permanent, unconfined) groundwater system to streamflow. It ensues where the Groundwater Store comes into play when the conceptual groundwater level is calculated to be at or above the stream invert. It is a function of the lateral hydraulic conductivity of the aquifer, the hydraulic gradient, and the discharge area along the stream. Salt brought about by surface runoff, interflow and groundwater flow is freely mixed in the stream zone.

Streamflow and salt load generated from each of the Response Units is routed downstream by Muskingum-Cunge routing scheme (Miller and Cunge, 1975). Before starting the daily loops, the model checks, organises, connects and develops all the links and processing order of the Response Units. Similarly, the model also organises and connects all the channel segments within both a Response Unit and the whole catchment, before streamflow routing starts. The time-step for streamflow routing was reduced to hourly from daily, primarily to avoid iterations and instability within the solution scheme. The overland flow routing is not considered, and the generated streamflow and salt loads are uniformly distributed along the stream channel segments within a Response Unit. Water and salt balances of lakes and reservoirs in the catchment are also computed.

C.1.11 Model 11: TOPMODEL

The grid-based TOPMODEL is based on three assumptions (Beven and Kirkby, 1979; Beven and Wood, 1983):

1. Surface runoff is generated when precipitation falls on a saturated portion of the catchment.
2. Subsurface flow at a given location depends on the saturation deficit at that point.
3. Saturated hydraulic conductivity exponentially decreases with depth in the upper soil layers.

Digital terrain data are preprocessed to obtain the catchment or sub-catchment distribution of a topographic index $\ln(a/\tan\beta)$, where a is the cumulative upslope area draining through a point (per unit contour length) and β is the local slope angle.

C.1.12 Model 12: SHE Model

The SHE model is a physically based distributed modelling system developed jointly by the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (Abbott et al., 1986). The movement of water within a catchment is modelled either by finite difference representations of the equations of mass, momentum and energy or by empirical equations derived from independent experimental research. The spatial distribution of catchment parameters, rainfall input and hydrologic response is achieved in the horizontal direction by setting a orthogonal grid network and in the vertical direction by a column of horizontal layers at each grid square. Each of the primary processes of the hydrological cycle is modelled separately, through:

- interception by Rutter accounting procedure
- evaporation by Penman-Monteith equation
- overland and channel flow by simplifications of the St Venant equations
- unsaturated zone flow by the Richards equation
- saturated zone flow by the two dimensional Bousssineq equations
- snow melt by an energy budget method.

Overall control of the parallel running of the components is managed by a FRAME component. Application of the SHE model requires large amounts of parametric and input data, some of which, like crop parameters, may be time dependent. Considerable computing resources are required to handle large arrays and to perform iterative solutions.

C.1.13 Model 13: TOPKAPI

The TOPKAPI model (Figure 21) is a grid-based simulation approach based on the idea of combining the kinematic approach with the topography of the catchment described by a DEM. The model has 10 components: interception, evapotranspiration, snowmelt, infiltration, interflow and percolation, vertical recharge to the water table, groundwater flow, surface flow, and channel flow, as well as lake/reservoir routing.

Interception includes rainfall and snowfall interception. For snowfall interception, TOPKAPI uses equivalent water depth to represent the snow pack on the vegetation instead of actual snow depth. Evapotranspiration can either be introduced directly as an input to the model by computing it externally, or estimated internally by a simplified equation derived from the radiation method (Doorenbos and Pruitt, 1984) and based on the air temperature and on topographic, geographic and climatic information (Todini, 1996). For different types of land use, monthly crop coefficients (Doorenbos and Pruitt, 1984; Maidment, 1993) are given, reflecting the state of plants in an annual growth cycle.

Because of limited data availability, the snow accumulation and snow melt component is driven by a radiation estimate based upon the air temperature measurements (Todini, 1996). The infiltration capacity depends on the land cover property and the soil moisture condition. By comparing infiltration capacity and the available surface water, the actual amount of infiltration is calculated. The unsaturated zone in the lower soil layer is considered as a transient transport zone, which transforms percolation to groundwater recharge if the soil moisture content of the upper soil layer exceeds the field capacity. The groundwater flow is generated from the groundwater saturated zone, which is the major source of channel flow during the non-flood season. Surface flow routing is performed by the kinematic approach (Wooding, 1965), in which the momentum equation is approximated by Manning's formula. For the channel flow component, the channel network is assumed to be tree-shaped, with reaches having wide rectangular cross-sections and the channel width increasing towards the catchment outlet. For lake/reservoir routing, a mechanism is developed for identifying the receiving cells and draining cells of the lake or reservoir in a distributed model.

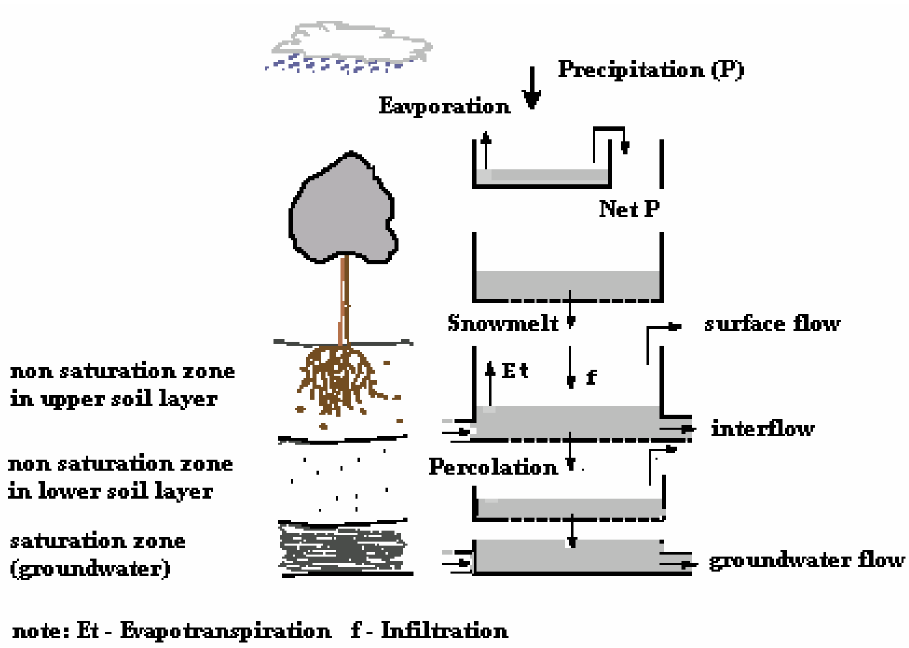

Figure 21. Water balance simulation in TOPKAPI model (Liu et al., 2005)

The data required for the TOPKAPI model include terrain data (DTM, DEM, land survey data), soil survey data, vegetation or land-use data, LAI data, precipitation data, evapotranspiration or air temperature data.

C.1.14 Model 14: CLASS

The following description of the CLASS model is taken from the CLASS User Guide. The CLASS modelling framework consists of a suite of tools that can be used for physically based distributed eco-hydrological modelling (Figure 22). The framework is designed for investigating the effects of land use and climate variability at both the paddock scale and the catchment scale. The framework includes the following tools that are used as building blocks in the catchment model (Tuteja et al., 2004).

CLASS Spatial Analyst. A fully automated GIS based tool required for spatial modelling (Teng et al., 2004). It prepares all spatial information required by the catchment model. This includes preparation of the climate surfaces and delineation of the climate zones, determination of the soil depth, a water balance computational sequence using multiple flowpaths from terrain analysis and flow accumulation areas, a wetness index, land

discharge areas, soil salinity distribution and mapping of pixels to land use and groundwater flow systems. A dynamic but constant user-specified pixel size can be used, depending on the DEM resolution and size of the problem.

CLASS U3M-1D. A variable sub-daily time-step model used for partitioning water balance in the unsaturated zone by using the Richards equation on a single pixel (Vaze et al., 2004b, released June 2004). Solutes are transferred between the soil materials by advection.

CLASS U3M-2D. A variable sub-daily time-step model used for partitioning water balance in the unsaturated zone by using the Richards equation on a hillslope (Tuteja et al., in prep.). Solutes are transferred between the soil materials by advection.

CLASS PGM. A daily time-step growth model based on the work of Johnson (2003). It simulates up to five multiple pasture species that may be summer or winter active perennial/annual pastures and legumes (Vaze et al., 2004a). Environmental conditions, as well as soil water and nutrient and salinity status, influence pasture growth and tissue dynamics.

CLASS CGM. A daily time-step growth model based on the work of Johnson (2003). It simulates a generic crop and its physiological structure and allows for complex interactions among light, temperature, available water and nutrients (Vaze et al., 2004b).

CLASS 3PG+. A monthly time-step growth model that simulates tree growth by using the 3-PG+ model (Morris, 2003), an adaptation of the 3PG model of Landsberg and Waring (1997).

CLASS Catchment Model. A distributed catchment-scale model that operates on a pixel level and makes use of the above tools. Climate data and landuse information are used at each pixel for plant growth using CLASS PGM, CGM and 3PG+. Unsaturated zone water and solute balance calculation is then performed, using U3M-1D along the vertical axis. Excess moisture and the associated solutes are then estimated over each soil material. Water and solutes are transferred from up-slope properties to the down-slope properties and eventually to the catchment outlet by using multiple flow paths and Darcian concepts. Additionally, spatial distribution of the soils, land use and climate and the groundwater flow system (GFS) links pixel-scale dynamics to the catchment-scale effects. Recharge and lateral throughflow each are pooled over the GFS. A proportion of each of these components is passed to the land as surface discharge and the remaining component is passed to the stream. Discharge to the land and stream is lagged appropriately and is based on the assumption that the bulk of the travel time results where the flow occurs under phreatic conditions, and that a fast-pressure transmission signal applies under the confined conditions. Routing in the stream is based on the response function approach (Nash, 1960; Kachroo, 1992).

Data requirements for CLASS are:

- maximum and minimum air temperature (ºC)
- rainfall (mm/day)
- pan evaporation (mm/day)
- shortwave radiation (MJ/m^2)
- vapour pressure (hPa)
- maximum and minimum relative humidity (%)
- digital elevation model
- data on groundwater flow systems
- distribution of soils
- soil salinity.

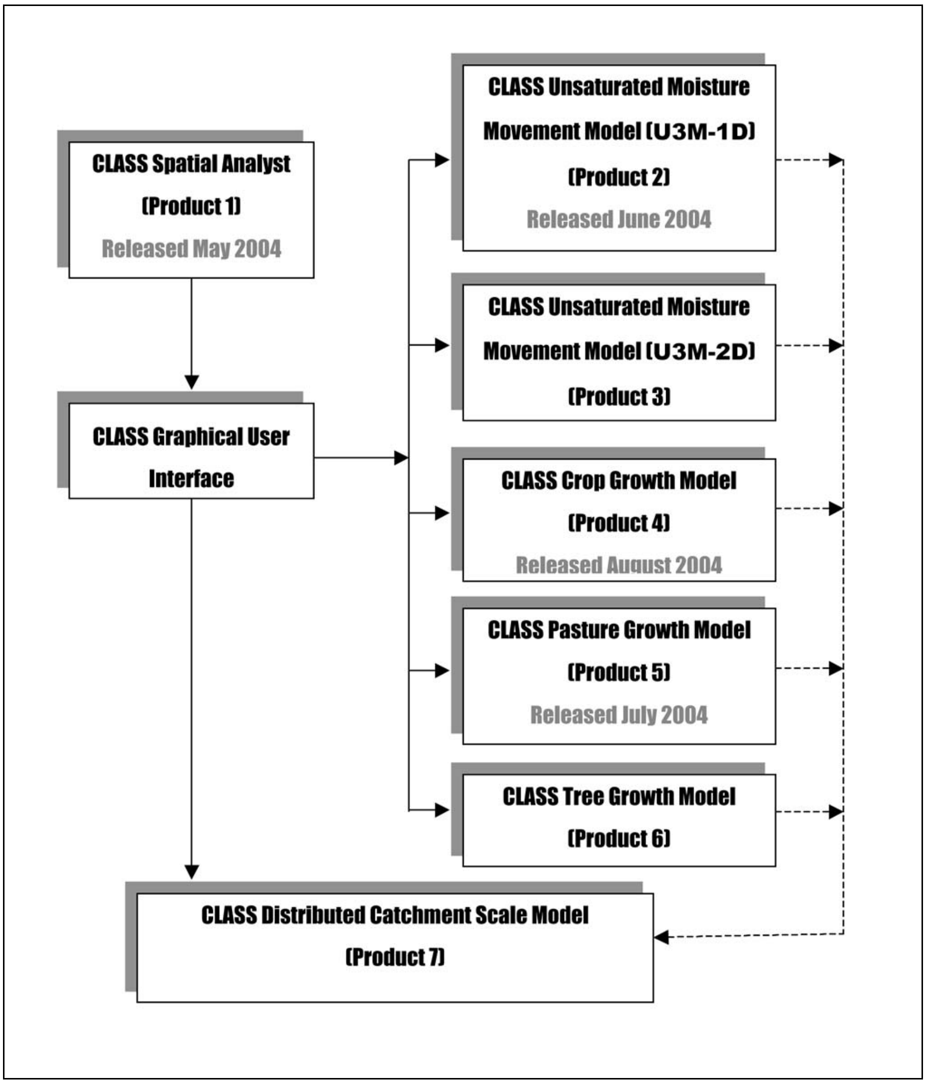

Figure 22. The CLASS modelling framework (Tuteja et al., 2004)

C.1.15 Model 15: WaterDyn

WaterDyn is a fully dynamic two-store water balance model developed for the Australian Water Availability Project (Raupach et al., 2008). The model requires gridded meteorological data and soil and vegetation property data, as well as observed stream gauge and land surface temperature from remote sensing for parameter estimation and model testing. The WaterDyn model models the movement of water in the (mainly) unsaturated soil column, spatially resolved across the Australian continent. This is defined by using two control volumes, consisting of 'shallow' (typically to 0.2 m depth) and 'deep' (typically 0.2 to 1.5 m) soil layers. The model state variables are the water stores (W_1, W_2) in these layers, or, equivalently, the relative soil water contents (w_1, w_2). A mass balance of water equates the change in the soil water store in each control volume to the sum of the water fluxes across the boundaries of the volume:

$$dW_1/dt = F_{WPrec} - F_{WTra1} - F_{WSoil} - F_{WRun} - F_{WLch1} \qquad (1)$$

dW_1/dt	F_{WPrec}	F_{WTra1}	F_{WSoil}	F_{WRun}	F_{WLch1}
Change of soil water in layer 1	Precipitation	Transpiration from layer 1	Soil Evaporation	Surface Runoff	Leaching from layer 1 to 2

$$dW_2/dt = F_{WLch1} - F_{WTra2} - F_{WLch2} \qquad (2)$$

dW_2/dt	F_{WLch1}	F_{WTra2}	F_{WLch2}
Change of soil water in layer 2	Leaching from layer 1 to 2	Transpiration from layer 2	Deep Drainage

The blue and red identify the input and output fluxes, respectively. Liquid water in aquifers, rivers and output fluxes is governed by mass balance in different control volumes outside those for soil water. Some of the outflow fluxes in Equations (1) and (2), such as surface runoff and deep drainage, are inputs to liquid-water control volumes.

Precipitation (F_{WPrec}) is an external input.

Transpiration (F_{WTra}), made up of contributions from each soil layer (F_{WTra1}, F_{WTra2}), is defined as the lesser of the energy-limited and water-limited transpiration rates. The energy-limited rate is defined by the Priestley-Taylor evaporation rate attenuated by the vegetation cover fraction (v), for reasons of both physics (Raupach, 2000, 2001) and simplicity. The water-limited transpiration rate in each soil layer is specified by using a rate parameter, kE, which controls the decay of water extraction by roots from a drying soil under water-limited transpiration and full vegetation cover.

Soil evaporation (F_{WSoil}) is the product of an upper-limit value (Priestley-Taylor evaporation), the relative water content in the upper soil layer raised to a power (a model parameter), and the fraction of bare soil ($1 - v$).

Surface runoff (F_{WRun}) is given by a step function: all precipitation runs off when the upper-layer soil is saturated, and there is no runoff otherwise.

Leaching (F_{WLch}) or drainage downward out of each soil layer is given by the product of saturated hydraulic conductivity and a power (γ) of the relative water content in that layer.

The sum of transpiration and soil evaporation is the total evapotranspiration, denoted $F_{WE} = F_{WTra} + F_{WSoil}$. The sum of surface runoff and deep drainage is the total runoff or local discharge flux of water from the soil column, denoted $F_{WDis} = F_{WRun} + F_{WLch2}$.

The total outflow from an unimpaired catchment (a catchment from which there is negligible water extraction for human use or retention by dams) is the lagged sum of surface runoff and drainage from the lower soil layer, for all grid cells in the catchment.

Total catchment outflow is computed in three steps. First, daily surface runoff and deep drainage for the whole catchment ($F_{WRun(C)}$ and $F_{WLch2(C)}$) are computed by averaging over all grid cells in the catchment, with area weighting:

$$F_{WRun(C)} = A_{(C)}^{-1} \sum_j A_{(j)} F_{WRun(j)}$$

$$F_{WLch2(C)} = A_{(C)}^{-1} \sum_j A_{(j)} F_{WLch2(j)}$$

where the subscript (j) denotes an individual cell, (C) denotes a whole-catchment average and

$A(j)$ and $A(C)$ are the respective areas (with $A(C)$ the sum of all $A(j)$ in the catchment).

Optionally, recursive lowpass filters are applied to $F_{WRun(C)}$ and $F_{WLch2(C)}$ to account for time lags between local runoff, local drainage and catchment outflow as gauged at the catchment outlet. Lowpass-filtered versions of $F_{WRun(C)}$ and $F_{WLch2(C)}$, denoted $Z_{WRun(C)}$ and $Z_{WLch2(C)}$, are defined by:

$$Z_{WRun(C)}(t_i) = \left(1 - \frac{\Delta t}{\tau_{Run(C)}}\right) Z_{WRun(C)}(t_{i-1}) + \frac{\Delta t}{\tau_{Run(C)}}(t_i) F_{WRun(C)}(t_i)$$

$$Z_{WLch2(C)}(t_i) = \left(1 - \frac{\Delta t}{\tau_{Lch2(C)}}\right) Z_{WLch2(C)}(t_{i-1}) + \frac{\Delta t}{\tau_{Lch2(C)}}(t_i) F_{WLch2(C)}(t_i)$$

where t_i is a time-step, $\tau_{Run(C)}$ and $\tau_{Lch2(C)}$ are the respective smoothing times for $F_{WRun(C)}$ and $F_{WLch2(C)}$, and Δt is the sampling time interval (1 day). The filters are initialised at $Z_{Run(C)} = 0$ and $Z_{Lch2(C)} = 0$. The filters are deactivated (that is, $Z_{WRun(C)} = F_{WRun(C)}$ and $Z_{WLch2(C)} = F_{WLch2(C)}$) when $\tau_{Run(C)} = \Delta t$ and $\tau_{Lch2(C)} = \Delta t$. The approximation in this approach is that a single time lag is used for all cells in the catchment, irrespective of their location with respect to the catchment outlet. Finally, the total catchment outflow or discharge is calculated as the sum of runoff and deep drainage for the whole catchment:

$$Z_{WDis(C)} = Z_{WRun(C)} + Z_{WLch2(C)}$$

On a typical workstation (2 Gflops s^{-1}) a continental run of 278,000 grid cells for 100 years takes about 60 hours of processing time.

C.1.16 Model 16: CABLE

CABLE is a model of biosphere atmosphere exchange allowing for interaction between microclimate, plant physiology and hydrology. The main features of CABLE are:

- The vegetation is placed above the ground, allowing for full aerodynamic and radiative interaction between vegetation and the ground.
- It is a coupled model of stomatal conductance, photosynthesis and partitioning of absorbed net radiation into latent and sensible heat fluxes.
- The model differentiates between sunlit and shaded leaves, i.e. it has a two-big-leaf submodel for calculation of photosynthesis, stomatal conductance and leaf temperature.
- The radiation submodel calculates photosynthetically active radiation (PAR) and near infrared and thermal radiation.
- The plant turbulence model by Raupach et al. (1997) is used to calculate air temperature and humidity within the canopy.
- Annual plant net primary productivity is determined from the annual carbon assimilation, corrected for respiratory losses. The seasonal growth/decay of biomass is determined by partitioning of the assimilation product among leaves, roots and wood. The flow of carbon between the vegetation and soil is described at present by a simple carbon pool model (Dickinson et al., 1998).
- A multilayer soil model is used. The Richards equation is solved for soil moisture and the heat conduction equation is used for soil temperature.
- The snow model computes the temperature, density and thickness of three snowpack layers.

C.1.17 Model 17: SIM (SAFRAN/ISBA/MODCOU) Model

The SIM system consists of a meteorological analysis system (SAFRAN), a land surface model (ISBA) and a hydrogeological model (MODCOU). It generates atmospheric forcing at an hourly time-step, and it computes water and surface energy budgets, the river flow at more than 900 river gauging stations and the level of several aquifers. SIM was extended over all of France in order to have homogeneous nationwide monitoring of the water resources. The SAFRAN analyses eight parameters: 10-m wind speed, 2-m relative humidity, 2-m air temperature, cloudiness, incoming solar and atmospheric radiations, snowfall and rainfall. These are computed every 6 hours and then interpolated to an hourly time-step. The ISBA land surface scheme is used in the NWP, research and climate models. In the SIM system, the three-layer restore model is used with the explicit multilayer snow model and the subgrid runoff and drainage schemes. The MODCOU hydrogeological model (i) computes the spatial and temporal evolution of the piezometric level of multilayer aquifers, (ii) computes the exchanges between the aquifers and rivers and (iii) routes the surface water within the river. The river flow is computed at 3-hourly intervals, and the evolution of the aquifer is computed daily.

C.1.18 Model 18: MIKE SHE

MIKE SHE is a fully distributed and integrated hydrological model developed by DHI (see www.dhigroup.com/Software/WaterResources/MIKESHE.aspx) on the basis of the SHE model. It is a spatially distributed model with GIS capabilities to capture the variability in soil, vegetation, rainfall, irrigation, drainage and other hydrological process that controls water movement in the x, y and z directions. Hence MIKE SHE can be used to simulate all of the processes in the land phase of the hydrologic cycle, including overland flow, channel flow, and groundwater flow in the saturated and unsaturated zone. MIKE SHE allows the simulation of all processes in the land phase of the hydrologic cycle (that is, all of the process involving water movement after the precipitation leaves the clouds; Figure 23).

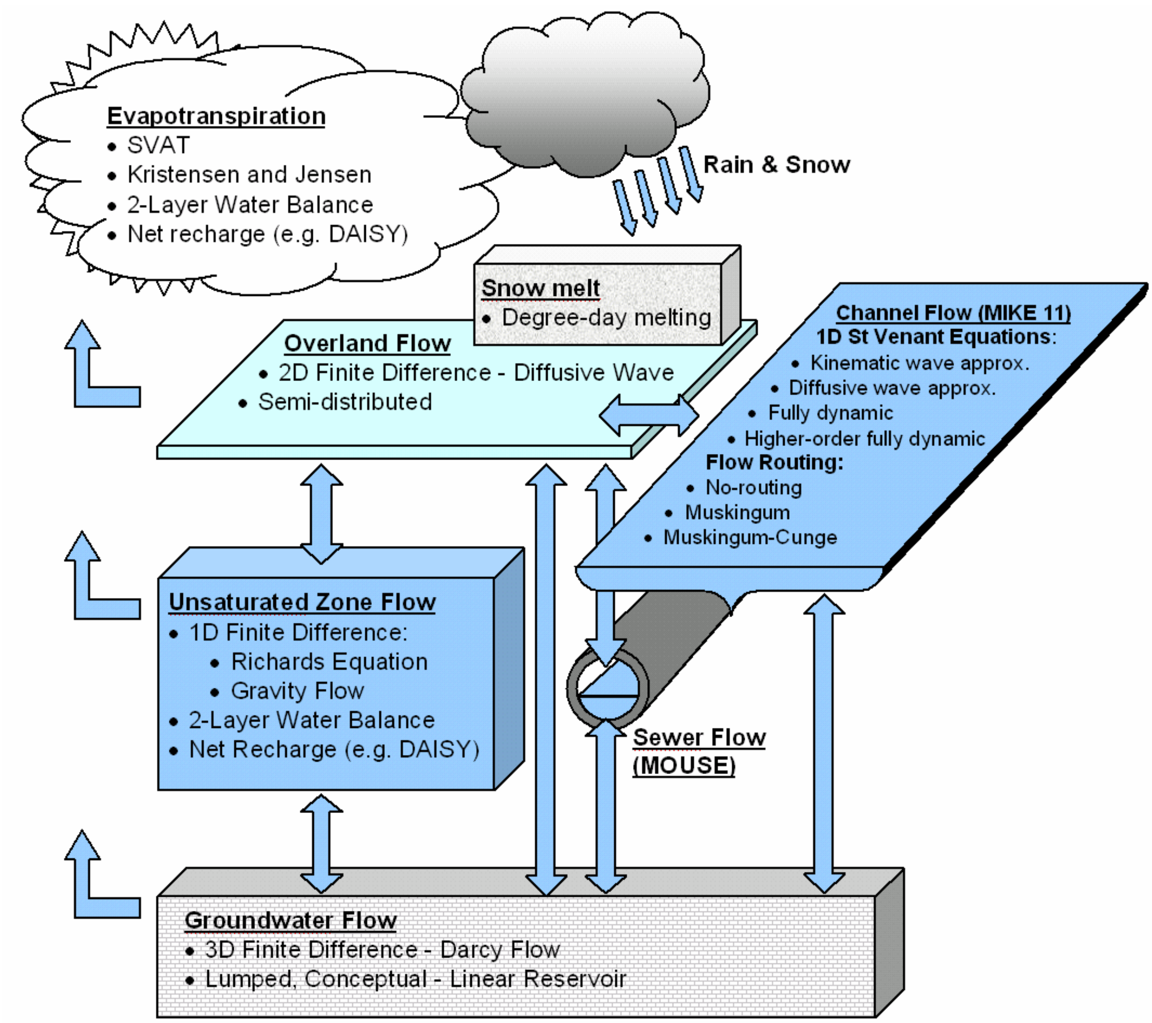

Figure 23. MIKE SHE hydrological process integration conceptual diagram

C.2 Comparison of rainfall–runoff models

Only a limited literature is available on the comparison of different rainfall–runoff models. WMO carried out a project on the intercomparison of 10 conceptual models used in operational hydrological forecasting (WMO, 1975). The 10 models were:

1. Bureau of Meteorology Model (CBM)
2. Girard I Model
3. Serial Storage Type Model (Tank I)
4. Serial Storage Type Model (Tank II)
5. Flood Forecasting Model (IMH2-SSVP)
6. Streamflow Synthesis and Reservoir Regulation Model (SSARR)
7. National Weather Service Hydrologic Model (NWSH)
8. Sacramento River Forecast Centre Hydrologic Model (SRFCH)
9. Rainfall Runoff Model of the Hydrometeorological Centre of the USSR(HMC)
10. Constrained linear Systems Model (CLS).

The comparison was carried out using data from six river catchments (Bird Creek, USA, 2344 km^2; Bikin River, USSR, 13,100 km^2; Wollombi Brook, Australia, 1580 km^2; Kizu River, Japan, 1445 km^2; Sanaga River Cameroun, 131,500 km^2; Nam Mune River, Thailand, 104,000 km^2).Not all of the models were run on all the catchments. Unfortunately, no definite conclusions were made from the comparison. Specific conclusions made with regard to each river are: The explicit moisture accounting models (NWS, SSARR, SRFCH, HMC, GIRARD I) have performed better for the Bird Creek (semi-arid region). All models performed well for Kizu River (humid conditions) and Sanaga River (equatorial and tropical). A number of recommendations were made with regard to the datasets used and future comparison projects.

Porter et al. (1988) attempted to predict rainfall–runoff model parameters from the taxonomic classification of landscape attributes for catchments in the Hunter Valley. The models used were the Australian Representative Basins Model (ARBM), the Hydrolog Model and the Sacramento model. Regression relationships for model parameter prediction were derived for the taxonomical indexes and more conventional attributes used in regionalization. The results indicated a slight improvement in the predictive ability of the taxonomic indexes over that of the conventional predictors, and the Sacramento model is marginally better suited than the other two to this application.

Franchini and Pacciani (1991) compared seven models using data for 4 months only from Sieve catchment in Italy. The seven models were:

1. Stanford Watershed Model
2. Sacramento Model
3. Tank Model
4. APIC model
5. SSARR Model
6. Xinanjinang Model
7. Arno Model.

The aim of the study was to assess (i) the ability of the models to reproduce the measured flows, (ii) the structure and the connection between the conceptual blocks of each model and (iii) the ease of calibration, estimation of parameters and their physical

interpretation. All the models except the APIC model produced similar and equally valid results in spite of the wide range of complexity. Complex models with a large number of parameters were found to be difficult to calibrate. The authors' final conclusion was that a conceptual model must balance two contrasting demands: greatest simplicity and to respect the physics of the rainfall runoff processes so that it is possible to use prior knowledge of the geomorphologic nature of a catchment in calibrating the model parameters.

C.3 National modelling efforts

An integrated groundwater/surface water hydrological model with a 1-km^2 resolution has been constructed for Denmark on the basis of MIKE-SHE, covering 43,000 km^2 (Henriksen et al., 2003). It is composed of a relatively simple root zone component for estimating net precipitation, a comprehensive three-dimensional groundwater component for estimating recharge and hydraulic heads in different geological layers, and a river component for streamflow routing and calculating stream–aquifer interaction. The model utilises a comprehensive database on geology, soil, topography, river systems, climate and hydrology.

A lumped parameter model of the contiguous USA has been developed by Arnold et al. (1999) using SWAT. The country was disaggregated into 78,863 sub-basins (average area 100 km^2) on the basis of soil type, and the elements of the hydrologic balance were estimated. There is no flow of groundwater between sub-basins.

The catchment model SWAT and the groundwater model MODFLOW with stream–aquifer interaction routines suitably modified were linked into a comprehensive basin model referred to as SWATMOD (Sophocleous et al., 1999). The hydrologic response unit concept was implemented to overcome the quasi-lumped nature of SWAT and represent the heterogeneity within each sub-basin of the basin model. The model was capable of simulating the surface water, groundwater and stream-aquifer interactions on a continuous basis for the Rattlesnake Creek basin in south-central Kansas.

The conceptual lumped parameter catchment model MIKE BASIN was applied to set up the nationwide water balance model (Vaitiekuniene, 2005) for Lithuania. A total of 66 gauged catchments have been delineated and the model was calibrated. For ungauged catchments, parameters from neighbouring catchments located in the same region were used.

TOPKAPI is used in the Republic of South Africa to estimate the soil moisture in near real time for the whole country. Liu et al. (2005) presented an application of the model wherein the model parameters are derived from public domain data on topography, soil and land-use types for the Upper Xixian catchment in China, with an area of about 10,000 km^2.

WaterDyn was applied Australia wide to estimate the runoff. A comparison with the observed data for about 200 unimpaired catchments showed that the model performed reasonably well. At the same time, off-line application of the CABLE model considerably overestimated the flows (Raupach et al., 2008).

Appendix D Farm dams (for private storage estimation)

D.1 Impact of farm dams

The impact of private storages on water balances in Australia is a component that is often overlooked during water balance calculations. This is despite a number of previous studies attempting to estimate the capacity and distribution of farm dams across a number of catchments. One of the findings regarding water accounting of SKM (2006) was that

'Volumes in major storages at any time are readily available. Capacities (but not volumes at a particular time) in minor storages (farm dams etc.) are available in some areas, and river and channel volumes are generally not available.

A comparison of water balances produced by 10 Australian water authorities [State Water, Sun Water, Goulburn-Murray Water, Southern Rural Water, Water Corporation (WA), Melbourne Water, Sydney Catchment Authority, Murray Darling Basin Commission, Hunter Water, Sydney Water] reveals that farm dams are not explicitly reported by any of the aforementioned authorities (Table 12). Water balance components such as 'Domestic and stock' and 'Irrigation' reported by some agencies may refer to some of the water used in farm dams, but this is not stated or quantitatively reported.

Table 12. Water balance components publicly reported by water authorities around Australia [from Sinclair Knight Merz (2005)]

	Water utility or authority									
Water Balance Component	State Water	Sun Water	Goulburn-Murray Water (2)	Southern Rural Water (3)	Water Corporation (WA)	Melbourne Water	Sydney Catchment Authority	Murray Darling Basin Commission (4)	Hunter Water	Sydney Water
Water Sources										
Start of year storage		✓	✓	✓				✓		
End of year storage		✓	✓	✓	✓		✓	✓		
Change in storage	✓				✓	✓	✓	✓		
Total inflows	✓	(1)	✓	✓		✓		✓		
- Storage inflows	✓		✓	✓						
- Unregulated inflows	✓		✓							
- Return flows			✓	✓						
Usage / Deliveries										
Total licensed consumptive usage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
- Irrigation		✓	✓	✓				✓		
- Domestic and stock			✓	✓				✓		
- Native title										
- Riparian rights										
- Urban		✓	✓				✓	✓	✓	
- Industrial		✓						✓	✓	
- Supplementary water / flood harvesting	✓									
Environmental water delivery	✓		✓		✓	✓			✓	
Storage releases for flood control						✓				
Storage releases for hydropower						✓				
Other		✓					✓			
End of system flows	✓		✓	✓						
Losses										
Total system losses					✓	✓			✓	✓
- Reservoir seepage										
- Reservoir net evaporation	✓									
- In-stream losses										
Reporting style										
Units	GL	ML	ML	ML	ML	ML	ML	GL	ML	ML
System by system reporting	✓	✓	✓	✓	✓	✓		✓		
% distribution of water by component	✓								✓	✓
% of water use metered					✓				✓	✓
Map or schematic						✓			✓	✓
Water balance	✓		✓					✓		✓

Notes:
(1) SunWater reports total available water allocated for consumptive use
(2) G-MW does not distinguish between gauged and ungauged inflows
(3) Referenced both annual report and resource manager's reports
(4) Referenced both annual report and Independent Audit Group's report on cap compliance

Farm dams are estimated to have a significant effect on streamflow. The National Water Commission (2007) estimated that every megalitre stored in private storages reduced streamflow by an average of 0.84 ML (although this ranged from 0.24 ML to 1.2 ML (Kollmorgen et al., 2007)). The National Water Commission (2007) also reported that in the Murray-Darling Basin 2200 GL can be stored in private storages, reducing annual streamflow by 1900 GL. It is estimated that the numbers and volume capacity of farm dams in the Murray-Darling Basin have increased by 37% and 48%, respectively over the 10 years to 2006 (van Dijk et al., 2006).

Previous research on the impact of private storages on a catchment scale (Letcher et al., 2001; Schreider et al., 2002) have attempted to determine the effects of the storages by analysing historical data and determining statistical trends. Letcher et al. (2001) notes that one issue with this approach 'is that reductions in potential streamflow response due to farm dam development are not directly distinguishable from the impacts due to other land use changes'. Neal et al. (2002) conducted an exhaustive search to find catchments where the gauging record and coinciding private storage construction would deem them suitable for a trend analysis. Only 11 catchments could be found where private storage development would likely exhibit a discernable effect on streamflow, and only two of the 11 catchments yielded statistically significant trends. Nathan et al. (2005) attempted to quantify the effects of private storages via hydrological modelling; they stated that 'simulation modelling affords an alternative approach to making inferences based on the statistical analysis of historic data'.

D.2 Methods of estimating farm dam storage

Research has previously been conducted on automating waterbody mapping from aerial photographs and satellite imagery. Dare et al. (2002) compared automated waterbody mapping via analysis of aerial photography and satellite imagery with mapping conducted by a human operator. The results suggested that waterbody mapping could be automated, but the cost of data acquisition was deemed to be far greater than the cost of automated or manual analysis. Aerial photography was costed at $8.00/km^2$, and IKONOS satellite imagery was costed at approximately $29.00/km^2$. One main restriction to automated private storage mapping is the resolution of the remote-sensing device. Work and Gilmer (1976) conducted waterbody mapping using remotely sensed data with a nominal ground resolution of 80 m by 80 m Landsat-1. It was concluded that, at this resolution, waterbodies above 1.6 ha could be consistently recognised but recognition of smaller waterbodies (0.4 to 1.6 ha) was dependent on whether the waterbody was wholly within one pixel or fractionally distributed over several pixels. Finch (1997) notes that the perimeter of smaller (or narrow) waterbodies will be more difficult to define than that of larger waterbodies. Finch (1997) also notes that some waterbodies that appeared on topographic maps could not be detected by satellite imagery, suggesting that the dams were no longer in use, either because of a failure in the dam or a switch to groundwater; it was further hypothesised that this demonstrated the ability of remote sensing to monitor surface water storage. One major shortcoming with using remotely sensed data to track changes in volumes of surface water is the limited ability to detect changes in small reservoir surface areas. Finch (1997) stated that waterbodies of 1000 m^2 and 3000 m^2 can be detected by using imagery from SPOT XS and Landsat TM, respectively. Using the formula of Lowe et al. (2005), these surface areas correspond to reservoirs of 1.27 and 5.37 ML, respectively. Stock and domestic storages are likely to be less than 5 ML in capacity (Lowe et al., 2005). Therefore, the volume of a stock and domestic storage would have to increase or decline by 25% for the change to be detected by analysis of SPOT XS imagery, whereas analysis of Landsat TM imagery would produce only a 'full' or 'empty' value for a stock and domestic storage.

Some private storage mapping has already been conducted by Australian State and Federal agencies. Geoscience Australia has completed mapping of waterbodies for a large

proportion of the Murray-Darling Basin (Murray Darling Basin Commission, 2008). The Bureau has this dataset (MDB.WaterbodyPolygon_25k) as a polygon layer file stored on the TAMBO server. The Western Australian Department of Water has conducted some mapping of farm dams in the South Eastern corner of the State. This dataset is available in ESRI shape file format at http://www.water.wa.gov.au/idelve/dowdataext/download/default.html. The Victorian spatial dataset (ANZLIC identifier ANZVI0803001018) contains spatial information on waterbodies, but because it has been derived from 1:100,000 maps it may not display many smaller waterbodies. A land-use map has been created from satellite imagery for the entirety of Tasmania. Waterbodies greater than 2500 m^2 are identified in the dataset, available from the GIS section of the Tasmanian Department of Primary Industries, Parks, Water and Environment. Additional work that has created datasets that may be of use in modelling the impacts that private storages have on the water balance include reports that assess the impacts of farm dams in Western Australia (Ritson, 2007), Victoria (Lowe et al., 2005) and the Murray-Darling Basin (Jordan and Wiesenfeld, 2007).

A number of studies have derived relationships used to determine the volume of an individual farm dam from the dam surface area; a review of these relationships can be found in the work of Jordan and Wiesenfeld (2007). These relationships are derived from survey data of a number of farm dams of varying sizes, which can then be extrapolated to other farm dams of known surface area. Lowe et al. (2005) derived a relationship from engineering plans obtained for 42 storages (predominantly >10 ML) from Victorian water authorities and further information from LIDAR remote sensing on an additional 110 storages (predominantly smaller dams than those for which there were engineering plans) in the Corangamite region in south-western Victoria. The resulting dataset consisted of 152 private storages ranging in volume from 0.4 ML to 420 ML. The surface area to volume relationship derived by Lowe et al. (2005) is:

$$V = 0.000145\ S^{1.314}$$

where V is reservoir volume in megalitres and S is surface area in square metres. This relationship had a Pearson coefficient value in log-log space of 0.95. This relationship was used by Sinclair Knight Merz (2007) instead of those that have been derived by other studies, because it was derived from a relatively large sample (152) using accurate surface area and volume estimates (from LIDAR and engineering plans). Lowe et al. (2005) also notes that there were no benefits in accounting for catchment characteristics with regards to improving the standard error. Catchment characteristics considered were elevation, slope, rainfall, evaporation, stream density, stream frequency, vegetation cover, depth to watertable and soil permeability (Lisa Lowe, Sinclair Knight Merz, pers. comm.). It is recognised that other relationships have been developed for other regions but there is currently no method for objectively comparing relationships; therefore, it is recommended that the relationship derived by Lowe et al. (2005) be used for the pilot studies. It is recommended that investigation of the adequacy of these relationships be tested following the pilot studies.

D.3 Mass balance calculation of change in storage for farm dams

Conceptually, the mass balance of farm dams (i.e. Inflows = Outflows + ΔStorage) can be expanded to:

$$P + (OLF + SSLF) + BF + PU\&RF = (E + SE + SP\&BP + U) + \Delta S$$

Inflow has been broken down into potential components, where P is precipitation directly on the reservoir surface, OLF and SSLF are overland flow and sub-surface lateral flow (which make up the quickflow component), BF is baseflow from an adjacent aquifer with a hydraulic head greater than the water surface of the reservoir and PU&RF refers to water pumped from a river or other source and the return flow from tailwater or downstream system components. Outflow has also been broken down into components where E is evaporation from the reservoir surface, SE is seepage, SP&BP is spillage

occurring when the storage is full and bypass flow occurring at any time, and U is water use. The remaining term ΔS represents the change in storage.

Precipitation directly onto the water surface can be included in net evaporation calculations. Overland flow and sub-surface lateral flow can be calculated as runoff from upland areas. Baseflow will also be generated from upland areas and therefore can also be included in runoff calculations. Pumping and return flow will be difficult to estimate and are also the only sources of water for certain dam types (e.g. turkey nests).

Evaporation from water surfaces is discussed in more detail in section 3.2.2 of this report.

With respect to large reservoirs, Sinclair Knight Merz (2005) reports that 'Seepage from reservoirs is almost never measured and is assumed to be zero, both because its volume is negligible relative to other water balance components and because it is difficult to accurately measure'. Actual seepage from private storages is unlikely to have ever been measured. Potential seepage may have been estimated from measurements taken before dam construction, but these measurements have most likely never been verified. Seepage is considered to be negligible within the TEDI Model (Neal et al., 2002). The primary factor controlling seepage from private storages is the saturated hydraulic conductivity (K_s) of the underlying soil, which is a factor of the soil texture. Soil texture varies spatially between different locations in a landscape and also between layers in a soil profile. Differences in soil texture can result in K_s varying by orders of magnitude. Estimates of soil texture (and thus K_s) for a particular location may be derived from existing soil maps, such as the *Digital Atlas of Australian Soil* derived from the work of Northcote et al. (1960–68). However, the estimates will have a high degree of uncertainty. It is also likely that overestimation of K_s may occur if the estimates are derived from low resolution soil maps. This is because dams are likely to be constructed in locations that have lower K_s than the surrounding area as an attempt to minimise seepage. An additional phenomenon has been observed in farm dams whereby a sealing layer develops in the soil near the soil water interface. These sealing layers can have a K_s of as little as 10% of the underlying soil. It has been hypothesised that the sealing layers are formed by either clay particles in the seepage water plugging micropores or stock compressing soil at the water's edge (Pepper, 1976). Milzow et al. (2009) used a spatially consistent K_s for modelling a heterogeneous aquifer, because precise information on the positions of the less permeable layers was unknown. Similarly, the spatial variability of K_s for soil under private storages is unknown. Milzow et al. (2009) also notes that, for modelling purposes, making spatial parameters variable 'would considerably increase the number of degrees of freedom but would not necessarily result in non-unique solutions during calibration, since the available observation data do not support the calibration of too many parameters'. Therefore, it is recommended that, if seepage is considered, a single figure for K_s be adopted for individual storages in a particular region for the purposes of calculating seepage.

Spillage will occur to all inflow when the dam is full. The proportion of dams with bypass facilities can be estimated from State and Territory registers of licensed farm dams. Private storages that are not required to be licensed are unlikely to have bypass facilities.

Water extracted from private storages for use has been calculated in the past by demand factors (Lowe et al., 2005; Nathan et al., 2005). A demand factor is the proportion of total reservoir volume (if available) that is likely to be used in a particular year or month. Demand factors vary with the primary purpose of the storage. It has previously been assumed that storages constructed for stock and domestic purposes are used consistently throughout the year (Lowe et al., 2005). This simplification is used because determining the true monthly use is not possible on a large scale. Storages constructed to supply water for irrigation have the highest demand during the period of irrigation.

Change in storage can be estimated from estimates of inflows or outflows or can theoretically be measured by monitoring of storage volumes. Monitoring of storage volumes is discussed further in section D.3.2.

D.3.1 Currently available techniques for estimating farm dam water flux components

Tool for Estimating Dam Impact (TEDI)

Inflows: Farm dam inflows in TEDI are calculated from current rain and the relationship derived from historic rain and gauged flows. Catchment areas for individual farm dams are assumed to be related to dam size, with a two-stage relationship (Nathan et al., 2005). TEDI requires the catchment area typical of a dam of 5 ML and a dam of 100 ML to derive these relationships (Sinclair Knight Merz, 2002). TEDI is not a spatially distributed model and therefore has no capacity to model the effects of 'cascading dams' (i.e. where one dam is below another), nor is there a capacity for dams to be filled by pumping. TEDI has no capacity for dams to be fed by groundwater. This should not be problematic, as the proportion of dams fed be permanent springs and the volume of groundwater discharged are unknown and not likely to be measured; therefore they cannot be confidently included in models.

Outflows: The primary outflow calculated by TEDI is water demand. Farm dams below a certain size are considered by TEDI to be for stock and domestic use. Lowe et al. (2005) determined (with regard to Victorian catchments) that 75% of dams with less than 5 ML capacity were used for stock and domestic purposes and 75% of dams with greater than 6 ML were used for irrigation and commercial purposes. Dams defined as stock and domestic have constant demand throughout the year. Lowe et al. (2005) states that the median annual demand for stock and domestic dams is 0.5 times the dam capacity: that is, a full dam contains 2 years of water for stock and domestic purposes, and monthly demand is therefore 0.042 times dam capacity. Farm dams that are primarily used for irrigation have monthly demands that differ depending on the seasonal demand of the irrigated crop.

Change in storage: Change in volumes in private storages can be calculated in TEDI.

Complex Hydrological Evaluation of the Assumptions in TEDI (CHEAT)

The CHEAT model has been used successfully to study the impact of farm dams on catchment streamflow. Nathan et al. (2005) used CHEAT to evaluate the simplifying assumptions inherent in TEDI. Three catchments (two in Victoria and one in South Australia) were used for the analysis. TEDI was initially run followed by five increasingly complex runs of CHEAT (Table 13). The results suggested that there were negligible differences in natural flow estimates derived from TEDI and the first three CHEAT scenarios for all three catchments. Estimates of the effects of dams on one catchment were improved via the CHEAT4 scenario. The estimates of the effects of farm dam impacts were more accurate for all three catchments in the CHEAT5 scenario as compared with the TEDI results.

Table 13. Simulation scenarios of CHEAT used by Nathan et al. (2005)

Scenario label	Dam volumes individually specified	Network topology defined	Non-linear scaling of streamflows	Upstream areas individually specified	Iterative solution for natural flows
TEDI	×	×	×	×	×
CHEAT1	✓	×	×	×	×
CHEAT2	✓	✓	×	×	×
CHEAT3	✓	✓	✓	×	×
CHEAT4	✓	✓	✓	✓	×
CHEAT5	✓	✓	✓	✓	✓

It is recommended that CHEAT not be considered as an existing modelling framework for estimating the effects of farm dams on the water balance. Nathan et al. (2005)

demonstrated that CHEAT was capable of producing statistically better estimates of the effects of farm dams on the water balance, but the additional data required to produce these estimates would be prohibitive when producing an account for the water balance of a large area.

D.3.2 Using a new methodology for estimation of farm dam water flux components

The Bureau may choose to produce a new methodology for private storage water balance. A new methodology has the ability to be tailored to the Bureau's output requirements and data availability. The obvious advantage of developing a new methodology is the ability to include components that do not exist in the currently available frameworks.

Inflows: Baseflow, pumping and return flow are potential inflows into private storages that are not considered by the existing TEDI and CHEAT frameworks. As previously mentioned, baseflow may be estimated as part of runoff. The process of return flow is unlikely to result in a net inflow into private storages, with the exception of tail dams; as return flow is usually re-used it can likely be accounted for as water use. The amount of water pumped into reservoirs may be estimated from water allocations delivered to the licence holders. It is recommended that the Bureau investigate the proportion of licensed water that is pumped into private storages for later use before attempting to account for this water.

Outflows: Evaporation, spills and bypass flows are outflows from private storages that are considered in the TEDI and CHEAT frameworks. As previously discussed, seepage is difficult to measure and verify. A new framework may produce a more accurate account of the water balance of private storages. The TEDI and CHEAT framework assume consistent water use from stock and domestic dams throughout the year. The survey results outlined by Lowe and Nathan (2008) suggest that only 66% of landholders use domestic and stock dams consistently throughout the year. A new framework developed by the Bureau may provide a better account of landholder habits, but this would be of benefit only if greater knowledge of landholder habits were available to the Bureau.

Change in storage: A new framework developed by the Bureau may have the capability to automatically include recorded changes in private storage volumes. The ability to use remote sensing to monitor small private reservoirs has increased in recent times with greater computer processing power and increasingly higher-resolution remote imaging. Finch (1997) demonstrated the ability to combine remotely sensed imagery with GIS software to monitor water levels in small reservoirs. Dare et al. (2002) used a similar technique for farm dam mapping in Australia. MDBC (Murray Darling Basin Commission, 2008) conducted waterbody mapping for a large proportion of the Murray-Darling Basin, and WIRADA aims to devise a methodology to map waterbodies across the entirety of Australia (Gonzalez et al., 2008). Such a methodology may provide the Bureau with the ability to use remotely sensed imagery to monitor changes in the storage volumes of private storages for the purposes of water balance accounting. However, images obtained by remote sensing may not be available at the temporal resolution desired by the Bureau (monthly or smaller) and may be affected by atmospheric conditions (e.g. cloud cover).

Appendix E River system modelling

E.1 IQQM

The Integrated Quantity and Quality Model (IQQM) is a water resources system model that has been developed and used by the NSW Department of Water and Energy (DWE) and its predecessors to simulate reservoir and river behaviour at a valley level (Simons et al., 1996) for the following main purposes:

- auditing compliance with policy objectives such as the Murray Darling Basin Ministerial Council (MDBMC) cap on diversions to 1993–94 levels
- helping river management committees in their input into Water Sharing Plans (a NSW Government initiative to help farmers in their investment decisions by fixing resource-sharing rules for a 10-year period)
- providing information for NSW interstate sharing management with Queensland and Victoria
- helping to plan better operating strategies and new infrastructure.

IQQM is based on a node-link concept (Hameed and O'Neill, 2005). The important features of a river system – such as reservoirs, irrigators and towns – can be represented by one of 13 node types. The movement and routing of water between nodes are carried out in the links. Generally the model is run on a daily time-step, but for the adequate representation of certain water quality and routing processes the model can be run on any time-step down to an hourly time-step. The water quantity module of IQQM simulates all the processes and rules associated with the movement of water through a river system. The major processes include:

- system inflows and flow routing
- on- and off-river reservoir modelling
- harmony rules for reservoir operation (operational management of multiple reservoirs, i.e. what and when to release from which reservoir)
- crop water demands, orders and diversions
- town water and other demands
- hydropower modelling
- effluent outflow and irrigation channels
- wetland demands and storage characteristics
- water-sharing rules for both regulated and unregulated river systems
- resource assessment and water accounting
- interstate water-sharing agreements.

The model applies hydrologic flow routing to the simulation of the different ranges of flow conditions. There are a variety of options available to model the different operating procedures of both on- and off-river storages. The options include Puls' routing, gated storage operation and target rule curves for flood mitigation and water conservation. IQQM can be configured for systems operating single or multiple reservoirs functioning in series or parallel. The irrigation module in IQQM includes features for soil moisture accounting; simulating famers' decisions regarding the area of crop to plant and irrigate; water ordering and usage (taking into account on-farm storage where appropriate); and accounting for uses related to water licences and access rules conditions. The model can also simulate fixed demands (e.g. urban water supplies and power stations), riparian and minimum flow requirements, floodplain storage behaviour, wetland and environmental

flow requirements, distribution of flows to effluent streams, and transmission losses. It is also capable of simulating water quality processes such as salinity, temperature and other constituents. In addition, the Sacramento rainfall–runoff model (Burnash, 1975) and climate generation model are both available as separate modules within IQQM. IQQM can also be directly linked with some of the Catchment Modelling Toolkit models, such as E2 and WRAM.

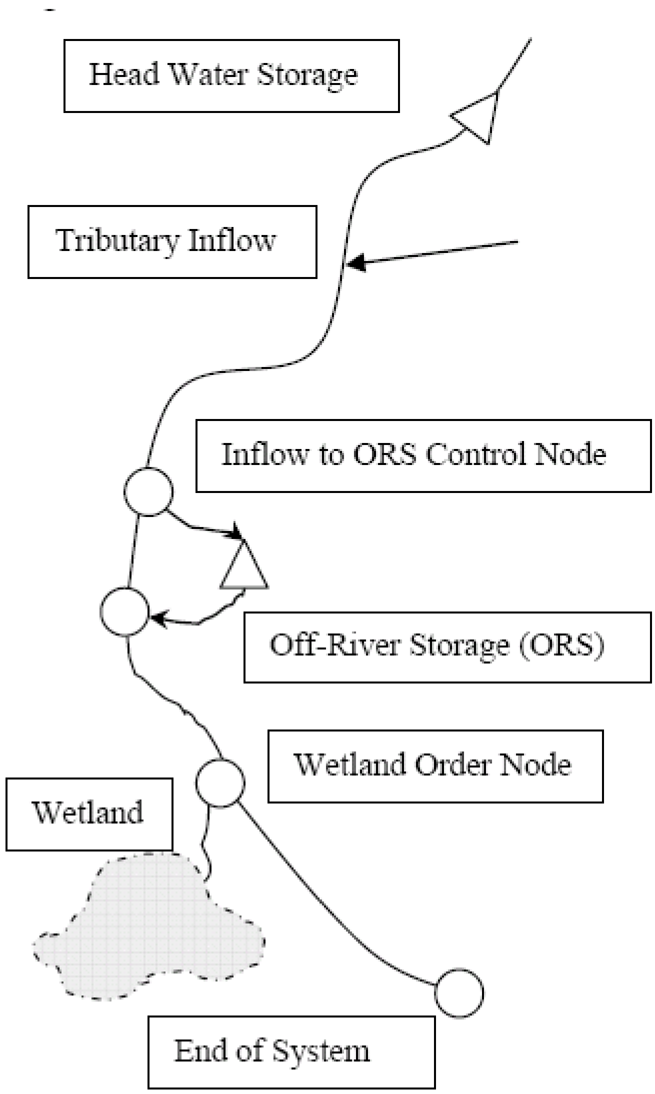

Figure 24. Example of a river system

E.2 REALM

REALM (REsource ALlocation Model) is a water transport system simulation package. It is general, in that any water transport system can be configured as a network of nodes and carriers representing reservoirs, demand centres, waterways, pipes, etc. REALM inputs include climate, streamflow, demand, discharges and management rules for the streamflow system, such as any requirements to pass environmental flows at particular stream locations. It is flexible in that it can be used as a 'what if' tool to address various options (new operating rules, physical system modifications, etc.). System changes can be quickly and easily configured and investigated. A wide range of operating rules can be modelled either directly or indirectly by exploiting the basic set of node and carrier types and their corresponding attributes. REALM uses a fast network linear programming algorithm to optimise the water allocation within the network for each time-step of the

simulation period, in accordance with user-defined operating rules. The user can specify the desired level of detail of output from the model. Output can be presented graphically, either in raw form or after post-processing using a suite of utility programs separate from the simulation model. Input and output data (ASCII) files have the same format and can easily be transferred to commercially available word processing and spreadsheet packages such as Microsoft Office to enhance presentation and/or to perform more detailed statistical analyses. The theory of REALM is given by Perera and James (2003).

E.3 River Manager

The eWater CRC is developing a software tool River Manager (see www.ewatercrc.com.au/reports/RiverSystemsTools_sep09-web.pdf), which is a model of water and management in river systems. The model will enable users to simulate the physical aspects of dams, canals, pipes and farming of any river network, and also the management aspects such as ownership, allocations and demand. The River Manager will reproduce the functionality of existing river models currently in use (IQQM, REALM and MSM-BIGMOD). A base model prototype will be developed by mid 2009, with trial and planning model prototypes being delivered in mid 2010 and 2011, respectively.

Appendix F Water use and population of the water balance tables

F.1 Introduction

Water use, both urban and rural, affects each of the stores defined in the water balances (Table 1 to Table 5) to different degrees, depending upon the nature of the area being considered and the dominant water use within that area. The majority of the water use–related terms fit directly into the Water transport system store; they include bulk urban water (S6), bulk rural water (S7), private irrigation (S8), private stock and domestic use (S9), private industrial/commercial diversions (S10), usage from private storages (S11), interbasin transfers (S12) and direct abstractions from groundwater (G6). These predominantly refer to the actual 'water use' or 'recipient consumption' component at the point where water is used. However, there are wider impacts, including fluxes and resulting influences on other stores, also associated with water use, which need to be considered when incorporating water use within a holistic water balance framework.

Rural water use – in particular agricultural use – will generate fluxes of water from surface (S6–S12) and groundwater (G6 and G7) stores in the form of abstraction and diversions; inputs to the landscape water store (T1–T4) from irrigation and other water use; and further potential inputs to groundwater (L4.2 and T9) through deep drainage and/or surface water stores (T5–T10) from irrigation runoff, depending upon the consumptiveness and nature of the agricultural practice. Additionally there will be losses from the water balance through direct open water evaporation from storages and irrigation channels and evapotranspiration through crop growth (see Section 3.2.2), combined with the interception impacts of farm dams (see section 3.4.5).

Similar principles can be applied to urban demands, although the outputs/wastewater discharges resulting from urban water use, particularly in major cities located in coastal areas, will be output from the water balance owing to discharge to sea. Direct abstractions and diversions will remove water from the Surface water and Groundwater stores into the Water transport system (T6 & G6). Leakage and distribution losses may provide inputs to the landscape (T2 & T3) and groundwater stores (T9). Outdoor water use within urban areas, for activities such as garden watering, will provide inputs to the land surface store. Different types of urban water use will require differing levels of consumption in terms of how much water is lost from the water balance altogether and is not included in sewage and effluent return flows. Recycled water use (in T3) will also need to be considered in both urban and rural environments.

As part of the development of the regional water balance framework, the following water use components (and related fluxes) will be included within the water balance calculations. Each of these terms will, or could potentially, contain a component of estimated water use, as they cannot be fully accounted for by the Water Regulations data alone:

- residential water use: general household water use, predominantly in the rural context with private supplies, but urban residential water use estimation may need to be considered.
- agricultural water use: covers a very wide range of agricultural activities, such as:
  - irrigated crops and produce (various)
  - livestock (various)
- commercial and industrial: encompassing a wide range of business activities.

Other significant water-use activities or consumers not explicitly included in the water balance framework include:

- mining operations
- electricity generation
- oil refineries and related activities
- forestry and plantation (indirect water use).

Under the Water Regulations, the Bureau will be receiving water-use or related information as under 3 categories of data: Category 5 – Water-use information; Category 7 – Information about urban water management; and also Category 6 – Information about rights, allocations and trades in relation to water. These data are described in more detail in Appendix A. These sources of data will not provide all of the water-use information for effective population of the water use and related terms of the water balances. As a consequence there is a need to develop methodologies to estimate the non-metered components of water use or those not specifically defined under the Water Regulations.

F.2 Water-use estimation – literature review summary

A review of existing water-use estimation methodologies has been carried out here, focusing primarily within Australia, but also considering relevant approaches applied elsewhere around the world. The following sections provide a brief summary of some of the preferred and most relevant methodologies, including the water-use elements considered and where they are applicable. An additional literature review can be found in the Rural Water Use Estimation Report (Parsons Brinckerhoff Australia Pty Ltd, 2008).

There are a number of methodologies used to estimate water use, both regionally and nationally. Most approaches apply a standard approach, which may be applicable nationally but requires regional- or local-scale assumptions, parameters or assessments for a more accurate calculation of water use. In most instances, the approaches are aimed at deriving water-use estimates for water accounting purposes or entitlement allocations, rather than specific water resource assessment and water balance applications. This tends to result in annual estimates of water use and would therefore require a temporal disaggregation method to generate reliable monthly water use estimates. The water accounting approaches also negate the calculation or estimation of all water fluxes relevant for a water balance calculation; for example, they do not always account for the difference between volumetric extraction and actual volumetric water use where the difference is accounted for by losses or inefficiencies.

The following water-use estimation methods cover regional estimation approaches, which define use rates on the basis of available metered water-use data for a related area or region. These rates are then applied to the non-metered water users, or are based on estimates using extensive water-use surveys, census data or other surrogate datasets. Modelling approaches that use related datasets, parameters and covariates are also described.

F.2.1 Experimental estimates of regional water use (Australian Bureau of Statistics, 2006)

This method, and others related to this, is based on the information acquired through the ABS Agricultural Census, Agricultural Resource Management surveys, other industrial and commercial surveys and national census information, undertaken periodically. The Census and surveys provide a very wide range of water-use data from a wide range of water users. With specific reference to agricultural water use, the data can provide very detailed information, such as the area of irrigated crops, the variety of crops, and also stocking

rates and types of livestock at the Water Management Area (WMA) and Statistical Local Area (SLA) level.

This approach provides methods for estimating a very wide range of water uses, including most rural (stock and domestic) uses, industrial and commercial activities, and residential water use. These methods have been applied in the production of the ABS Water Accounts and have also been refined to provide increased levels of detail for AWR 2005.

The main issue with this method is the underlying assumption that water-use rates are consistent across an entire State, WMA and/or SLA for a similar industry or user; this does not take into account the variability in water use due to climatic and geographic differences. However, improved statistical techniques have been developed to allow water-use estimates to be derived at smaller spatial scales, with potential reductions in overall uncertainty. Where there are numerous commodity types within a defined area, the error can be less than 5%, but in areas with limited production of certain commodities the error may be greater than 25%. Uncertainty estimates will be clearly linked to spatial scales of water-use estimates and the balance between the scale/accuracy of survey and census data when applied to smaller areas such as small river catchments and the spatial applicability of the underlying assumptions at different locations.

This method is relatively straightforward to implement and provides a very detailed assessment of individual farms in terms of understanding the individual farming practices, the size of the landholding, and the sources and use of water. The data collated from the ABS census and surveys provide a valuable source of national water-use patterns. However, these data could potentially be enhanced by being combined with, and related to, other non-ABS data, regulations datasets and water use estimation methods. The application of this approach, or the use of the related data within other water-use estimation methods, is clearly very dependent upon having sufficient access to the ABS datasets.

F.2.2 Water Resources – guidelines on amounts of water reasonable for uses (Australian Capital Territory Government, 2007)

This is the method used for planning and allocation of access entitlements to water resources in the ACT. It covers most types of water use, including rural stock and domestic, residential gardens, sports grounds, and non-metered agricultural and horticultural use. The ACT water-use guidelines apply a mix of regional estimates, per unit area, industry type or population, but also apply a more dynamic approach for the estimation of agricultural and horticultural water use.

Rural stock water-use requirements for a property are determined from the stock-carrying capacity of a lease and from the average consumption by different stock of varying age ranges, or by the ACT average stock watering requirements. The domestic component is based on a standard annual water use per unit area, which may be varied on the basis of local conditions where sufficient data are available.

The irrigation requirement is based on the FAO methodology (See Section F.2.5), which is a widely used and robust approach for estimating crop water requirements using environmental, physiological and meteorological factors and measurements. A key component of this approach is the assessment of evapotranspiration, which therefore needs to be considered in conjunction with the methods described in Section 3.2.2.

Water-use requirement assumptions for different animal stocks (per unit area domestic use) and crop factors for irrigation are defined for this methodology and represent ACT-specific assumptions. Their application is designed to be valid for the ACT area, but it can be compared with assumptions applied across the States or with similar assumptions that may be applied locally within ACT.

F.2.3 NSW Reasonable Use guidelines (NSW Farmers Federation, 2007)

This method is used only in NSW to estimate unlicensed stock and domestic water use for surface water and groundwater. It is a similar method to that used by the ACT for allocating access entitlements (see above). This approach also assigns an annual volume (ML/ha) to stock water demand on the basis of differing climatic conditions and stocking rates. The domestic water demand component applies an annual assumption based on the number of people per landholding and the area of land/gardens.

The method can be applied to rural and peri-urban regions, and adjustments can be made for climatic and stock water demand differences. GIS systems could be used to map values at a catchment or basin level. The method can also be used as a rapid assessment of quantification; however, ground truthing may be required to provide better confidence in the results, which are thought to have an estimated error of between 30% and 50%.

The method does not differentiate between surface water and groundwater use, and broad assumptions on domestic use are likely to produce overestimates. Moreover, the method is not sensitive to changes in usage patterns over time.

The two 'reasonable use' methods described above provide rapid annual assessments of water use for rural and peri-urban situations, given that additional information on the landholding, entitlements and permits is known. The required information may be available from the ABS datasets and from data provided under Category 6 (information about rights, allocations and trades) through the Water Regulations. Similar methods with varying assumptions are expected to exist for other States, and these will be collated fully through the project to provide a source of comparison with other water use estimation methods. The nature of reasonable use estimates, which, in these examples, apply the same assumptions State wide, will inherently have greater levels of uncertainty.

F.2.4 Estimates for stock and domestic use (Lowe et al., 2009a)

This approach provides a methodology for estimating stock and domestic (S&D) water use at a very small spatial scale and has been applied to the Werribee catchment in Victoria as part of a detailed water accounting and uncertainty study. Using estimates based on both demand requirements and supply assumptions allows an improved estimate of uncertainty; also, where applicable, the estimates may be reconciled to further improve the accuracy of the overall estimate. However, the nature of the approaches and the scales applied in this example means that there is a requirement for more detailed site-specific information, such as the identification of entitlements for individual land-owners, and analyses such as farm dam modelling. These requirements may not be feasible to apply at a national scale. A brief summary of the two approaches is given below.

Demand-based estimates

Using ABS census and survey data, this method estimates the number of households not connected to an urban water supply within statistical local areas (SLAs), and then applies an area weight disaggregation method to obtain the number within the catchment or study area. It further reduces the number of households through the use of ABS census statistics that describe the percentage of households that use rainwater tanks for water supply. A household water-use coefficient (assumed to be equal to the average water use in the State) is then applied to the final number of properties to get the domestic water-use figure.

Stock water use is estimated by the same method, using ABS Agricultural Census data that give a breakdown of the different numbers and types of stock within each SLA. Stock water coefficients are based on the average stock water rates published by the relevant department in each State.

Supply-based estimates

This method bases water use on extraction/diversion licenses, and also on an additional approach for estimating usage from farm dams within the catchment or study area.

Licensed S&D water use is simply calculated on the basis of the number of licensed extractions/diversions and assumes that each license uses the full entitlement annually (without exceeding the entitlement). Water usage from farm dams is estimated by the TEDI model. The number of farm dams in the catchment is identified from topographical maps and compared with more accurate information. It is also assumed that larger dams are used solely for irrigation and are not included in the estimation of S&D use.

The TEDI model estimates net inflows to the farm dams on the basis of runoff for the entire catchment apportioned to each dam. A demand factor (average volume extracted from the dam annually) is then applied to all dams to calculate the final water-use figure. The demand factor is based on research by relevant departments/utilities in the State, although this research will not necessarily be done for all regions/States around Australia.

F.2.5 Estimation of crop water requirements and consumptive use – The FAO Methodology

Within the water balance, the irrigation water-use term (T1) is predominantly related to water use in order to maintain actual evapotranspiration (AET, or the consumptive use of the crop) at the optimum level for a defined crop type. This is in order to maximise crop growth and therefore the financial return and efficiency of water use. The calculation of crop water requirements is also used in the design and planning of irrigation and drainage systems. Various empirical, analytical and theoretical equation approaches have been derived to estimate AET (referred to here as ET_{CROP}); these approaches are widely used by irrigators and individual farmers across the world at various scales, for a wide variety of crop types and across the range of climatic regimes. This approach is also recommended by the Department of Primary Industries in Queensland for use by agricultural and horticultural water users (Hare, 2008).

The FAO methods allow the estimation of potential evapotranspiration (PET) to be used for the calculation of reference evapotranspiration (ET_o = PET), which is then transformed using crop coefficients (kc) to calculate the relevant crop water requirements ET_{CROP}.

$$ET_{CROP} = kcET_O \text{ mm/day}$$

The first step is the calculation of ET_o. A wide variety of approaches exists; each derives ET_o by using different available datasets and measurements that apply physically based and empirical principles. The three generally applied approaches for estimating ET_o are: 1) The FAO Penman-Monteith equation; 2) the Blaney-Criddle formula; and 3) Pan Evaporation techniques using predefined pan coefficients. If the FAO methodology is to be applied for estimating irrigation water use for the water balances, then the ET_o used will need to be consistent with the ET-related data derived for other components of the water balance. These are covered in more detail in Section 3.2.2.

The second stage of the FAO methodology requires the conversion of ET_o to ET_{CROP} by using a constructed crop coefficient (kc) curve, as shown in the ET_{CROP} calculation equation above. The curve represents the changes in the crop coefficient over the length of the growing season. The shape of the curve represents the changes in the vegetation and ground cover during plant development and maturation that affect the ratio of ET_{CROP} to ET_o. From the curve, the kc factor and hence ET_{CROP} can be derived for any period within the growing season, as shown in Figure 25. This also allows water use for irrigation to be estimated at a monthly or even daily time-step.

Significant research has been carried out in an attempt to define crop coefficients and related curves for major crop types in a wide range of countries and climatic regions. The research incorporates other related factors and can be found in FAO Irrigation and

Drainage Paper No. 24 (Doorenbos and Pruitt, 1984) and Paper No. 56 (Allen et al., 1998).

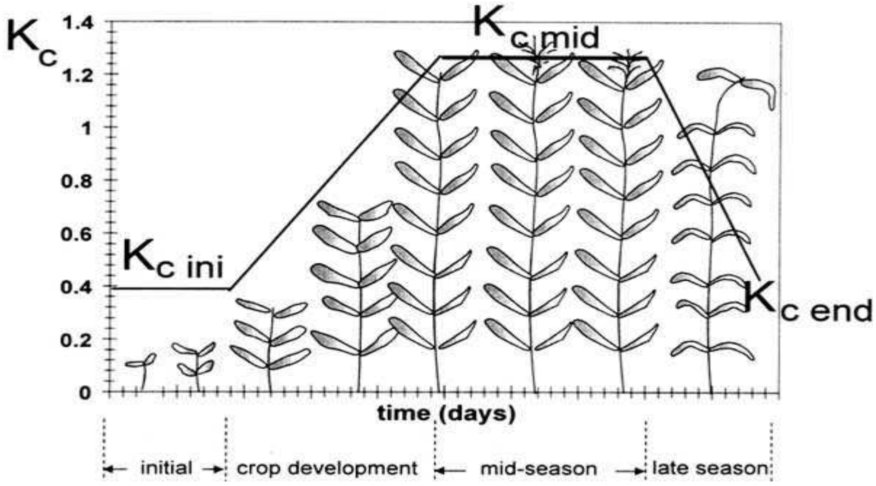

Figure 25. Example of a crop coefficient curve.

In order to effectively apply this approach to the estimation of irrigation water use, it is still necessary to acquire additional information relating to rainfall, crop types, irrigation application methods and the area of irrigated crop in order to derive a volumetric water use. Other relevant spatial climatic data relating to PET and rainfall will be available as part of the requirements for other modelling methods such as rainfall–runoff modelling.

The estimation of water use on the basis of the calculation of AET and crop water requirements, such as by the FAO methodology described above, has been applied practically in Murray-Darling Basin Sustainable Yields studies, described below, which also looked at alternative estimates of AET using remotely sensed data and parameters.

F.2.6 MDBSY – monthly water accounts (CSIRO, 2007)

A methodology was defined to estimate actual water use for the Murray-Darling Basin monthly water accounts. Net use of surface water is calculated as the difference between monthly rainfall and monthly actual evapotranspiration (AET).

AET estimates are based on a combination of:

- remotely sensed surface temperate, combined with spatially interpolated climate variables to estimate AET from the surface energy balance; and
- the FAO56 'crop factor' approach, which scales interpolated PET by using remotely sensed estimates of soil moisture and surface greenness.

The two methods are constrained by using ground-truthed AET measurements at seven study sites and streamflow observations from more than 200 catchments across Australia. Both methods provide AET estimates at 1-km resolution. Spatial estimates of water-use are aggregated for each river reach, and separately for floodplains and wetlands and for areas classified as irrigation. Uncertainties in the spatial estimates originate from interpolated climate and rainfall data, as well as from remotely sensed observations and the spatial estimates of land surface classifications.

Additionally, for the Murray-Darling water balance account, where monthly irrigation diversion data were available they were used directly. In the case of New South Wales, only annual diversion data were available, and they had to be disaggregated from annual to monthly series by using an indirect estimation method. This was done by first estimating the actual evapotranspiration in irrigation areas by using remote sensing, as

described above. The distribution of monthly diversion through the year was assumed to be proportional to the distribution of monthly differences between the actual

$$Q_{divert,i} = Q_{divert,Ann} \frac{(AET_i - P_i)}{\sum_{j=1}^{12}(AET_j - P_j)}$$

evapotranspiration and the rainfall, using the following formulae:

$$(\mathrm{AET_i} - \mathrm{P_i}) > 0$$

$$\mathrm{Q_{divert,i}} = 0 \qquad\qquad (\mathrm{AET_i} - \mathrm{P_i}) \leq 0$$

where $Q_{divert,i}$ is the diversion in month i, $Q_{divert,Ann}$ is the annual diversion, AET_i and P_i are the actual evapotranspiration and precipitation in month i, respectively, and the sum $\Sigma(AET_j - P_j)$ is taken over the year but only for the months in which evapotranspiration is greater than precipitation.

In this example AET was derived by using remotely sensed data, However, this method could be applied by using any of the AET estimates described above (or those described in Section 3.2.2), and it provides an effective and efficient approach to temporarily disaggregating annual irrigation diversions or water use. Most major irrigation water users will be providing measured water-use data directly, but the nature or form of the data may mean that adjustments are needed to provide monthly distributions of water use. This approach may also be applied to measured data in order to validate and check monthly data that may be erroneous or missing. Where crop types are known, this approach could be further enhanced by applying the relevant crop coefficients (kc).

The approaches used to estimate irrigation water use on the basis of AET from remotely sensed data in the Murray-Darling basin, and also from other estimates based on PET and ET_o data, are heavily reliant on having access to detailed information relating to farm location, size and crop types in order to derive a meaningful estimate of volumetric water use. This highlights the fact that the survey and census data collected by the ABS (as described in Section F.2.1) will also be required for applying this approach. There may also be the need for spatial GIS datasets representing irrigation areas, although the availability of these data for the whole of Australia is not known.

F.3 Summary of water use estimation methods

The methodologies described provide a brief assessment and description of a sample of water use estimation methods applied across Australia, but in no way do they represent all available techniques. Many approaches are inherently consistent with each other, and in all cases there is a clear dependency on covariate datasets to provide a basis for estimation of water use. It is noted that methods for water use estimation are being developed as part of the WIRADA WRAA project (Shao et al., 2008). Furthermore, water use estimation methods are being developed in house and will be described within a Water Use Estimation Methods Review document (Steven Boxall, pers. comm.), to be completed following the 2009 pilot studies.

Table 14 provides a summary of the methods described and indicates the types of water use they can be used to estimate. It also shows the relevant States or scales they may applied to.

Table 14. Summary of the water use estimation methods

Method	Region in which applied	Domestic	Stock	Irrigation / agriculture	Commercial, industrial & municipal
ABS – Experimental estimates of regional water use	National State Regional	Yes	Yes	Yes	Yes
NSW reasonable use	NSW	Yes	Yes	–	-
ACT reasonable use	ACT	Yes	Yes	Yes	Some (sportsgrounds & gardens
Demand and supply based estimates	VIC (Werribee Catchment)	Yes	Yes	–	–
Crop requirements and consumptive use – FAO	Worldwide National Catchment Field	–	-	Yes	–
MDBSY monthly water accounts	Murray-Darling Basin	–	-	Yes	–

F.4 Other components and fluxes associated with water use – rural and urban

In order to effectively incorporate water use within a water balance, additional terms, components and fluxes that are not explicitly represented in the water use estimation approaches defined above need to be estimated and defined. These primarily relate to connecting water use estimates to fluxes within a water balance. These fluxes include losses and leakage, deep drainage and runoff from irrigation areas, illegal water use, theft and operational water use. At this stage the current level of understanding relating to these additional non-metered demand components and fluxes, as well as the ability to quantify, measure and model them, is very limited. These fluxes, in combination with estimates of changes in internal storage, allow the water use water balances to be defined, thus enabling them to be integrated more effectively with the overall regional- or catchment-scale water balances.

For example, the water balance for a defined irrigated area from extraction to water use and related returns, for a specified period, can be described by the following equation:

$$\mathrm{ABS} - \mathrm{L} = \mathrm{I} = \mathrm{AET} + \mathrm{SD} + \mathrm{DD} - \Delta\mathrm{SWC}$$

where ABS = Abstraction, extraction or diversion to an irrigation area

L = Losses, including conveyance losses, through leakage and evaporation

I = Irrigation

AET = Actual evapotranspiration

SD = Surface drainage

DD = Deep drainage beyond the root zone (or upflow if negative)

$\Delta\mathrm{SWC}$ = Change in soil water content (final minus initial) in the root zone.

AET represents the water use, or local demand, in order for a particular crop to grow at the required rate, whereas I represents the irrigation application rate or volume, where the water irrigation process is not 100% efficient. As described in previous sections, there is significant research and modelling focusing on calculating AET, which can be relatively

easily defined on the basis of measurable variables and parameters. However, the remaining components are subject to high levels of uncertainty and variability, particularly as deep drainage, surface drainage, losses and the change in soil water content cannot be easily measured and errors in the calculation will directly affect the estimation of other variables. Generally, where AET for a crop has been estimated for irrigation purposes the volume extracted or used will be greater than required so as to compensate for these inefficiencies and losses.

Within the urban context the water balance from extraction to water available for use can be represented by the following simplified equation for a system where there is not assumed to be any internal change in storage over time:

$$\mathrm{ABS} = \mathrm{WAFU} + \mathrm{RWOU} + \mathrm{DSOU} + \mathrm{L}$$

where ABS = Abstraction, extraction or diversion to an irrigation area

WAFU = Water available for use

RWOU = Raw water used operationally, including treatment works loss

DSOU = Distribution system operational use, including mains flushing

L = Distribution losses, including losses on trunk mains, service reservoirs and distribution mains.

The nature of these components, combined with limited monitoring and lack of detailed research at a national scale (possibly with the exception of research on urban water system losses), makes the spatial and temporal variation almost impossible to represent explicitly without significant uncertainty in the estimates. Therefore, the pilot water balance studies will attempt to acknowledge and represent these components, and the assumptions used may be tested on the basis of any existing studies and research. In the urban balances the leakage components will need to be consistent with those presented in the national water performance reports produced annually by the Water Services Association of Australia (WSAA) and Essential Services Commission (ESC).

A few examples of the related non-metered demand components and fluxes (along with references to relevant research) that may be able to inform these assumptions are provided below.

F.4.1 Losses

A detailed national study is being carried out as a key component of the Irrigation Infrastructure Hotspots Assessment Project (Hotspots Project) (CSIRO, 2008a) under the 'Sustainable Rural Water Use and Infrastructure' element of Australian Government 'Water for the Future' program, with significant input from CSIRO. This study aims to develop consistent methods for identifying the nature, location and amount of water losses (real and apparent) in existing channel and piped irrigation delivery systems across Australia. The key component of the work will aim to develop strategic water balances on a site-by-site basis to identify all of the micro-components of irrigation water systems in order to quantify water loss and inefficiency components in a top-down approach, as highlighted in

Table 15.

Table 15. Conceptual model of the water balance components of an irrigation system (CSIRO, 2008a)

<table>
<tr><td rowspan="11">Inflows to the System</td><td>Water Diverted from river</td><td rowspan="2">Authorised deliveries</td><td rowspan="2">Water delivered to growers

Water traded out to other districts

Water delivered to other authorised users</td><td rowspan="2">Metered and other diversions</td></tr>
<tr><td>Water traded in from other districts</td></tr>
<tr><td rowspan="4">Groundwater abstraction</td><td rowspan="9">Water Loss</td><td rowspan="6">Apparent losses</td><td>Escapes</td></tr>
<tr><td>Over-flows</td></tr>
<tr><td>Metering inaccuracies</td></tr>
<tr><td>Channel filling</td></tr>
<tr><td rowspan="5">Rain on supply system</td><td>Channel emptying</td></tr>
<tr><td>Theft</td></tr>
<tr><td rowspan="3">Real losses</td><td>Seepage</td></tr>
<tr><td>Leakage</td></tr>
<tr><td>Evaporation</td></tr>
</table>

The water loss components of the conceptual irrigation system are separated into the 'apparent' and 'real' losses. The real losses are of most importance with regards to attempting to quantify or estimate specific flux components of the water balance framework. The apparent losses (in particular metering inaccuracies) will need to be considered and may best be represented within the uncertainty component of the individual water balance terms. The remainder of the water balance will be determined either directly from the regulations data (particularly Category 5 data) and/or by using water use estimation methods as described in the previous sections.

The ongoing research and results of this study can be used to inform the development of our water balances (particularly for rural and irrigation water use) with respect to losses, as well as other components of demand. The current status and availability of data is not known but can be assessed in the coming months with regards to the data relevance, use and application.

Losses and leakage from water company distribution systems will be incorporated under non-revenue water within the Water Regulations datasets, but the degree to which this is disaggregated is not known at this time. The accuracy and approaches used to estimate the non-revenue water volumes will also need to be investigated to ensure consistency and reliability of estimates between different companies and water providers. Water utility leakage is published in the Water Services Association of Australia (WSAA) and Essential Services Commission (ESC) National Performance Reports, and these data can be used to apply consistent estimates of leakage where possible.

F.4.2 Deep drainage

Various field experiments have been carried out to try to quantify the additional components of the irrigation water balance, and many of these have utilised field lysimeters, which allow accurate measurements of numerous variables and fluxes within the irrigation water balance to be measured. Several Australian studies have specifically looked at the deep drainage water flux under irrigated crops (Humphreys et al., 2003; Bethune et al., 2008); the studies have related this to the overall water balance and have identified key dependent variables. These studies may be able to inform an assumed deep drainage flux component for the pilot water balances, but as it stands there is no reliable approach that can be reliably applied; therefore, this term may be omitted until further research becomes available.

F.4.3 Surface drainage

Surface drainage, or irrigation runoff, will be influenced by numerous factors, including irrigation method and rate, soil type, topography and soil moisture conditions. It may be possible to derive an estimated volume or proportion based on metered return flows data where available, or alternatively this may be possible to estimate on the basis of the factors used to derive natural runoff to streamflow in non-irrigated areas (See Appendix C).

F.4.4 Meter errors

The incorporation of meter error and meter accuracy will be covered in more detail in future, as this falls under uncertainty within the water balance (see section 2.5.2). However, a brief summary of relevant projects is included, because metering uncertainty is an inherent part of applying and using metered water use data and relationships to estimate non-metered water use within a water balance.

Various studies, both within Australia and internationally, have looked at the accuracy and reliability of water meters. The Department of Environment, Water, Heritage and The Arts (DEWHA) engaged SKM in Oct 2007 to conduct a stocktake of Australia's Non-Urban Water metering Systems (Sinclair Knight Mertz, 2008). The stocktake will inform the implementation of metering standards under the National Water Initiative (NWI). This study of water metering assets could be combined with an additional study commissioned by the NWC of 'Improving in-field verification of non-urban water meter accuracy' (National Water Commission, 2008) and also with the Audit of Murray-Darling Basin Cap (Marsden Jacob Associates, 2005). These studies and water company internal reviews can be used to apply assumptions and uncertainty profiles for metered data within the water balances. Additional information should be available from the National Measurement Institute and Standards Australia.

F.5 Water use estimation recommendations

For the pilot studies it is proposed that non-metered water use be estimated on the basis of a combination of the ABS approaches described above, together with local and regional water use assumptions; FAO-type water use and crop water requirement methods should also be applied. The requirements for estimating industrial and commercial water use are less well understood at this time, and the preferred methodology is expected to evolve as the scope and scale of requirements for this component of water use become more defined. The Water Regulations datasets for metered water use will also be used to inform the non-metered components where data are of sufficiently good quality and given that reliable relationships between the usage types can be defined and identified from the available data. The proposed water use estimates are:

- rural stock and domestic: apply existing and newly derived regional and local stock water use assumptions to generate a demand-based estimate that can be reconciled against supply-based estimates where sufficient data are available. Locations and stock rates and types are to be derived by using ABS survey and census datasets. Domestic consumption is based on assumptions and data relating to people per landholding and size of garden up to a maximum limit. Temporal disaggregation to monthly data may be required on the basis of climatic or other covariates.
- rural agriculture: apply a combination of the ABS approaches and FAO-type water use and crop water requirement methods, using relevant data available from ABS agricultural and water use surveys. This may allow estimates to vary depending upon irrigation methods etc.
- industrial/commercial: this is inferred from local or regional measured water users of a similar or same industry type (scaled if required) on the basis of the ANZSIC system. Use applicable ABS datasets if available.

- residential water use: this is estimated on the basis of local/regional household or per capita consumption estimates obtained from relevant water company performance reports (i.e. WSAA or ESC). These may need to be applied on the basis of previous year data if the final figures have not been released for the water balance year under consideration.
- mining and other very large water users: at this stage it is not clear whether or not these data will be included under the Water Regulations data. This information may need to be estimated on the basis of ABS accounts and assigned a fixed water use profile throughout the year (i.e. production and therefore consumption are assumed to be constant).

The above methodologies will assist in the derivation of water use estimates, but they will not directly provide all of the components of demand and the associated fluxes and inter-relationships between the water balance stores. At this stage it is proposed that they be based on assumptions derived from existing studies and research, with acknowledgment of the uncertainty related to the assumptions and possible sensitivity testing. The assumed components will include:

- irrigation losses from open channels: these are based on existing investigations such as the CSIRO Irrigation Hotspots study, including evaporation losses, leakage and other losses. Losses from irrigation channels may also be possible where the Water Regulations data are of sufficiently high accuracy.
- deep drainage from irrigated areas: assumptions are based on lysimeter and other experiments within Australia, although this is not assumed to be a significant component of the water balance and is particularly difficult to quantify, measure or model in reality.
- run-off and return flows from irrigated areas: these are assumed from the available Water Regulations data if the quality of the available data is suitable. It may be possible to relate this information to agricultural practices and other physical variables such as soil types and antecedent soil moisture conditions when the data are required at less than annual resolution.
- leakage and losses from reticulated distribution systems (rural and urban): this information is assumed on the basis of previous studies and investigations. Urban water providers may be able to supply this as a component of non-revenue water and should incorporate assessments of leakage and losses in their annual performance reviews.

The proposed approaches remain very simplified at this stage, but it is planned that these will be further developed over time on the basis of improved understanding and the increased availability of relevant and reliable data. They should also be supported by ongoing research being carried out by CSIRO through the WIRADA framework.

Appendix G Water fluxes and storage in groundwater systems

G.1 Generation of a groundwater-level surface

G.1.1 Definition and discussion of what is required

Watertable and potentiometric surfaces are a fundamental input to hydrogeological investigations; they are needed as inputs for the estimation of both groundwater storage and regional flow. A continuous surface of groundwater elevation can be generated from groundwater levels measured in bores at a point by contouring manually or by using spatial interpolation methods and packages. Some of the options for, and considerations associated with, interpolating groundwater levels are presented in Table 16.

Table 16. Considerations and options for interpolation of groundwater levels

Factors for consideration	Options
Interpolation technique	Hand contouring Spline Topo to Raster (ANUDEM) ANUSPLIN Kriging Ordinary kriging Universal kriging Co-kriging Kriging with external drift (KED)
Choice of dependent variable	Depth to groundwater Groundwater elevation
Input data requirements – spatial resolution	Number of points Distribution
Input data requirements – temporal resolution	Selected month Selected season Historical data Transformation of historical data to represent current month
Input data requirements – accuracy	Surveyed reference point Reference point estimated from DEM
Ancillary data options – type	Ground surface elevation DEM Stream water level Lake water level TOPMODEL index Geology/hydrogeology
Ancillary data – method of use	Synthetic data points Secondary variable Regression analysis with primary variable Map algebra
Interpolation software options	ArcGIS Spatial Analyst or Geostatistical Analyst ANUSPLIN R Surfer MODFLOW

G.1.2 Input data

Measured groundwater levels are the primary inputs to groundwater interpolation. Ancillary data, such as ground surface elevation and surface water levels, can also be used. The availability and quality of bore data are the greatest challenges for groundwater interpolation. Some of the problems commonly associated with measured groundwater levels include:

- irregular and inadequate spatial distribution
- irregular and inadequate sampling frequency
- error associated with measurement
- difficulty in identifying the screened aquifer
- bore location poorly defined
- reference elevation (m AHD) not surveyed.

However, there are several methods for increasing the availability of bore data:

- inclusion of bores without a surveyed height datum (i.e. surface or reference elevation is estimated from a DEM)
- inclusion of bores with water levels measured at a date other than the one being interpolated (i.e. use all available measurements or use temporal extrapolation/interpolation or relationships between climate and water level to estimate the water levels) (Peterson and Barnett, 2004)
- use of dummy bores in data-poor areas (Salama et al., 1996).

G.1.3 Options for interpolation

There are many techniques for interpolating groundwater levels; some of these techniques are briefly described below, and their advantages and disadvantages are summarised in

Table 17.

Method 1: Manual contouring

Manual contouring involves drawing contour lines based on interpretation of water level measurements. Contour lines can then be digitised and converted to a grid by using standard GIS software, such as Topo to Raster in ArcGIS. Manual contouring is time-consuming and cannot be automated, although it does allow expert knowledge of hydrogeology to be incorporated into the output surface.

Method 2: ANUDEM and Topo to Raster

ANUDEM is a thin-plate smoothing spline designed to produce hydrologically correct Digital Elevation Models or DEMs from irregularly spaced point or contour data (Hutchinson, 1989). Thin-plate smoothing splines fit a surface by reconciling the error at the points and the overall smoothness of the surface. The key features of ANUDEM are:

- As the watertable is generally considered to be a subdued replica of surface topography, ANUDEM can be a useful tool for interpolating groundwater levels. There are several examples in the literature of ANUDEM being used to create groundwater surfaces. Peterson (2005) used ANUDEM to create a watertable grid for Wabasha County, Minnesota, using a range of inputs, such as groundwater levels, soils mapping and elevation of perennial streams, lakes and wetlands. In Australia, ANUDEM was used to create watertable grids from groundwater and river level measurements in the Murray-Darling Basin Sustainable Yields Project (Parsons et al., 2008).

- The Topo to Raster tool in ArcGIS is based on ANUDEM. The default parameters in Topo to Raster will generally produce a reasonable groundwater surface, and consequently it is easy to automate the production of groundwater surfaces with Topo to Raster.

However, some of the features of ANUDEM, such as the enforcement of connected drainage features, are not suited for the interpolation of groundwater levels. Additionally, ancillary data such as surface elevation cannot be included in the interpolation as secondary variables or covariates.

Method 3: ANUSPLIN

ANUSPLIN is another thin-plate smoothing spline, but, unlike ANUDEM, it can incorporate additional variables or covariates (Hutchinson, 2007). It has been used extensively to interpolate temperature and rainfall surfaces using surface elevation as an additional variable (Hutchinson, 1995; Jeffrey et al., 2001), but it has not been widely used to generate groundwater surfaces. Littleboy et al. (2001) undertook a comparative study for methods for interpolating groundwater levels in the Macquarie catchment, New South Wales. They reported that ANUSPLIN produced poor results compared with kriging.

Method 4: Kriging

The Kriging interpolation method is being more commonly applied to the interpolation of groundwater levels (Salama et al., 1996; Desbarats et al., 2002; Peterson and Barnett, 2004). It is a geostatistical technique that models an output surface based on the structure of the input data, as defined by an experimental variogram (Figure 26). A variogram represents the correlation of data values at points as a function of distance between the points.

The variogram model (e.g. linear, spherical, exponential, circular) is fitted to the experimental or measured variogram points, and the result is then used to interpolate between measurement points and produce an output surface. Consequently, kriging requires a much greater understanding and analysis of the input data than most other approaches. This can make it difficult to automate.

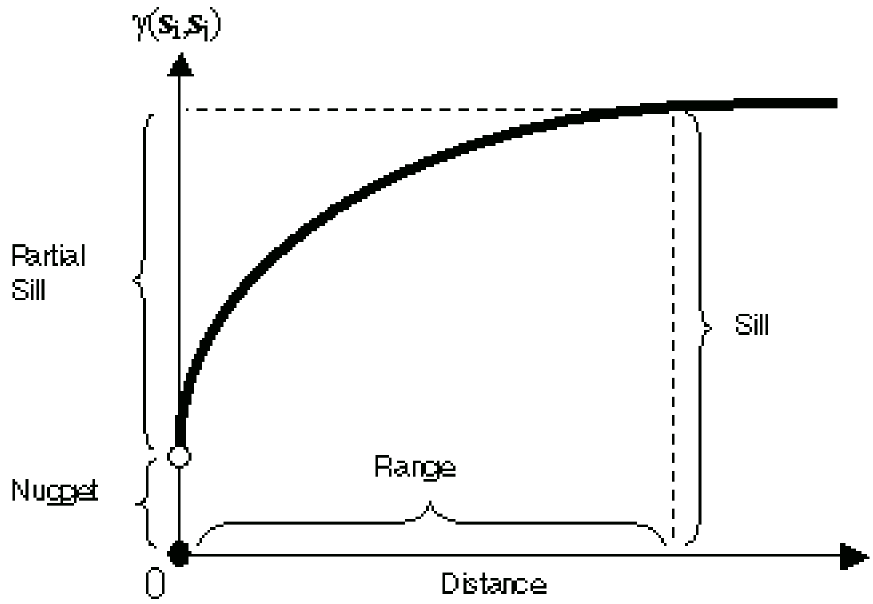

Figure 26. Example of a semivariogram

There are several types of kriging, as summarised in Table 18. Each type has previously been used to interpolate groundwater levels. Co-kriging and kriging with external drift allow additional data (typically ground surface elevation) to be used in the interpolation.

Table 17. Selected methods for interpolating groundwater levels

Method	Description	Advantages	Disadvantages
Hand-contouring	Manually drawing of contours based on interpretation of observations	Able to incorporate expert knowledge Can perform well with few data points	Cannot be automated Performed poorly in comparative studies
Topo to Raster	Based on ANUDEM, a thin-plate spline designed to create hydrologically-sound DEMs from point and contour data	Can be easily automated Specifically designed to create DEMs Quick and easy to use Can also be used to create a grid from watertable contours Error diagnostics	Secondary variables and covariates cannot be incorporated
ANUSPLIN	Thin-plate smoothing spline	Ancillary data can be used as a secondary variable or covariate Error diagnostics	Parameters must be determined for each region to fully exploit technique Software must be purchased Poor results in a comparative study
Kriging	Geostatistical approach that interpolates on the basis of the structure of the input data	Powerful statistical technique Industry standard Performed well in comparative studies Able to incorporate ancillary data Error diagnostics	Requires detailed understanding of input data and interpolation technique Parameters and model must be determined for each region Difficult to automate Requires large amount of input data Time consuming

Table 18. Comparison of different types of kriging

Type	Description	Comment
Simple kriging	Assumes that there is a known constant trend	The assumption that the trend is known is unrealistic
Ordinary kriging	Is the most common type of kriging and assumes that the constant trend is unknown and must be estimated	There must be enough observations to estimate the variogram
Universal kriging	Assumes a general linear trend model	
Co-kriging	Based on ordinary kriging, but introduces a covariate. There is explicit structural dependence between the target and auxillary variable.	
Kriging with external drift	Estimates the target variable by using a denselysampled auxiliary variable (known at all locations).	

Method 5: Regression against topography

As the watertable is often a subdued replica of the topography, another option is to derive a relationship between depth to groundwater (or groundwater elevation) and surface elevation measured at bores (Figure 27). This relationship can be used to derive a groundwater elevation grid from a DEM. Salama et al. (1996) used this technique in the Cuballing catchment in southwest Western Australia. They established three significant relationships between groundwater and surface elevation on the basis of data from only the Cuballing catchment (r = 0.78), four catchments in the WA wheatbelt (r = 0.95), and the WA catchments plus one NSW catchment (r = 0.99).

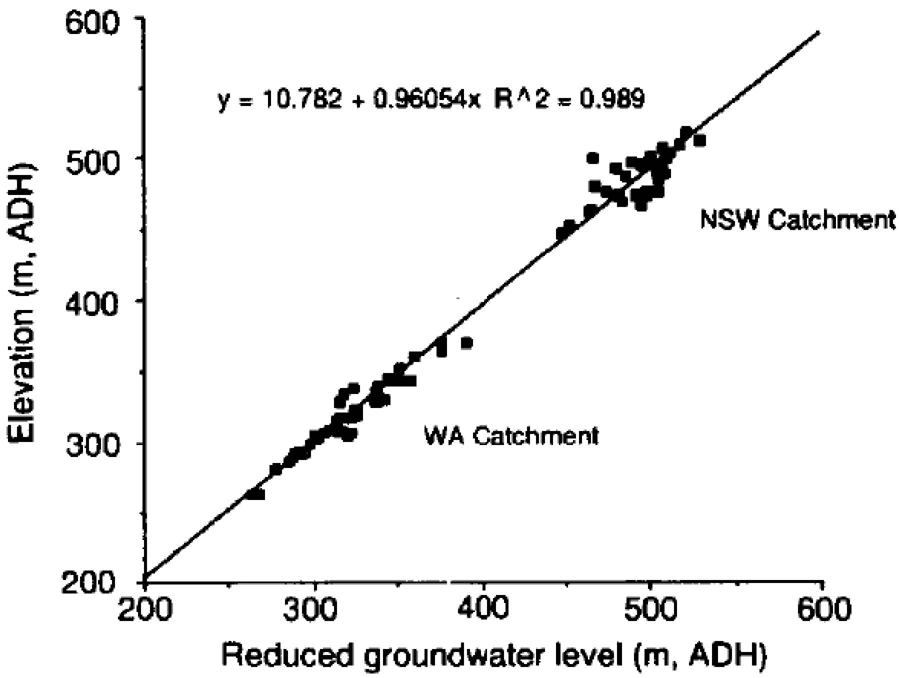

Figure 27. Regression analysis between surface elevation and reduced groundwater level (Salama et al., 1996)

Method 6: Data-poor regions

Different approaches will be needed in data-poor regions. Some of the potential options include:

- use of representative bores selected on the basis of data quality, hydrogeology and physiography
- weighted averaging of bores in the aquifer, with weights based on hydrogeology and physiography
- use of relationships between depth to groundwater and surface elevation established in areas with similar hydrogeology and physiography (after Salama et al. 1996).

G.1.4 Method evaluation

Based on an assessment of the interpolation methods against a range of criteria, ANUSPLIN, Topo to Raster and the kriging methods are all potential options for interpolating groundwater levels. It is difficult to recommend a single technique without a comparative study of the different methods. Therefore, it is recommended that a comparative study be undertaken in the Murrumbidgee catchment to compare the most promising methods.

The criteria that will be used to assess the performance and accuracy of the different methods include:

- error diagnostics provided by software
- difference between the watertable elevation grid and DEM (for watertable only)
- residual calculated at a selection of points not used in interpolation
- comparison with an understanding of hydrogeology, such as the location of recharge and discharge areas and differences in hydraulic conductivity
- comparison with the locations of surface drainage features and with what is known about groundwater–surface water connectivity.

G.2 Groundwater storage

G.2.1 Definition of groundwater storage and discussion of what is required for estimating catchment water balance

The term 'groundwater storage' is used to describe both the total volume of groundwater within an aquifer, including water retention (known as total storage), and the volume of groundwater that can be removed by pumping (referred to as extractable storage). 'Extractable storage' is a term commonly used in studies estimating the available groundwater resource. In contrast, total groundwater storage is analogous to surface water storage terms in the Bureau's water balance framework, which include dead storage (Barratt, 2008). It is important to recognise that neither of these terms represents the volume of groundwater that can be extracted from an aquifer in a given year; this volume is strongly dependent on the nature of the aquifer and the number and location of groundwater extraction bores.

G.2.2 Previous national and regional assessments

Groundwater storage has not been routinely estimated in Australia, although groundwater storage terms have been included in some national and regional water assessments, such as the AWR 2005, MDB Sustainable Yields Project, ABS Water Accounts and NLWRA 2001. Groundwater storage was not evaluated in the AWAP or Water 2010 (

Table 19).

Groundwater storage terms were included in the opening and closing balance for the AWR 2005. The definition and methodology for calculating these terms recommended in the discovery phase of the project were:

'*Aquifer storage is the volume of saturated media between the water table in an unconfined aquifer and the aquifer base multiplied by aquifer storativity. The change in aquifer storage through time can be estimated in the GIS using a time-invariant aquifer base surface but time-varying hydraulic head surfaces. A uniform storativity value can be used or a spatial distribution estimated across the GMU if data is available.*'

In the regional assessments, groundwater storage terms were populated only for NSW regions. Groundwater storage was estimated for the watertable aquifer to a depth of 20 m, either as total storage using porosity or active storage using specific yield. The estimates were given a reliability rating of C or ± 50%. For other parts of Australia, groundwater storage was not estimated because of lack of data or because groundwater is not managed to trigger levels; hence the term was considered irrelevant.

In the MDB Sustainable Yields Project, only the change in groundwater storage was reported for high-priority aquifers. This term was modelled using MODFLOW.

For the NLWRA 2001, the sustainable yield was determined instead of the aquifer storage:

'*Total storage volume of groundwater aquifers was not determined, as it was not considered to be a particularly useful measure from a water management or use perspective*.'

Sustainable yield was defined as the level of extraction that should not be exceeded in order to protect the values associated with the aquifer.

The ABS Water Accounts report on water stocks. Groundwater stocks were not included in the 2004–05 Water Account owing to the lack of data. In the 2000–01 Water Account, the sustainable yield data from the NLWRA 2001 was used as a proxy for groundwater stocks:

'The volume of groundwater that exists in Australia is not known with certainty. The volume changes as water percolates through the ground to aquifers (underground water resources) and through water being extracted (e.g. from bores). In the past, instead of an absolute measure of groundwater stock, a proxy has been used. That is the amount of water that can be sustainably extracted, referred to as sustainable yield.'

Table 19. Inclusion of groundwater storage terms in national and regional water assessments

Study	Term	Definition	Method
AWR 2005	Water in store: • renewable non-saline groundwater • renewable saline groundwater • non-renewable groundwater	The volume of saturated media between the water table in an unconfined aquifer and the aquifer base multiplied by aquifer storativity	Volumetric calculations
ABS Water Account 2000–01	Water stocks		Sustainable yield from NLWRA 2001 is used as a proxy.
ABS Water Account 2004–05	–	–	–
NLWRA 2001	Sustainable yield	Level of extraction measured over a specified planning time frame that should not be exceeded to protect the higher value social, environmental and economic uses associated with the aquifer.	
AWAP	–	–	–
Water 2010	–	–	–
MDBSY	Change in storage		Estimated as the difference between gains and losses modelled using MODFLOW.

G.2.3 Alternative methods

Methods 1–3: Volumetric calculations

Both total and extractable groundwater storage can be estimated by simple volumetric calculations based on aquifer area (A), saturated thickness (b) and aquifer properties, i.e. effective porosity for total storage (n_e) or specific yield (S_y) and storage coefficient (S_s) for extractable storage. The equations are presented in Table 20.

Table 20. Methods for estimating groundwater storage.

Storage term	Aquifer type	Equation	References
Method 1. Total storage	Unconfined, Confined	$V_T = A \times b \times n_e$	(White and Reeves, 2002; Reppe, 2005)
Method 2. Extractable storage	Unconfined	$V_E = A \times b \times S_y$	(Dixon, 2003)
Method 2. Extractable storage	Confined	$V_E = A \times b \times S_s$	(Dixon, 2003)

Other hydrogeologists prefer to consider groundwater storage relative to a management or even an arbitrary level (Method 3). For example, in AWR 2005, groundwater storage for NSW was assessed relative to a depth of 20 m. In this case, it is the change in storage rather than the volume that is important. One of the benefits of this approach is that only the depth to groundwater is needed (rather than the groundwater elevation), and hence bores without a surveyed reference elevation can be used.

Input data

The required data for volumetric calculations of groundwater storage include:

- Most of these datasets will ultimately be provided by Geoscience Australia as part of the Groundwater Geofabric Project. However, interim data sources are required for the pilot study and first WRA.
- The groundwater storage terms included in the Bureau's water balance framework discriminate between saline/non-saline and renewable/non-renewable aquifers as well as aquifers within/outside Groundwater Management Units. The data and estimation techniques for categorising aquifers also need to be considered.

Method 4: Analysis of River Baseflow

During periods when there is effectively no precipitation (and no other significant catchment water inputs), the water flow observed in a river can be assumed to result primarily from drainage of groundwater from the upstream riparian aquifers in the catchment. One of the most widely used equations in engineering practice to describe such flow, also referred as baseflow, is of the exponential decay type (Brutsaert, 2008):

$$y = y_0 \exp(-t / K) \qquad (1)$$

Where:

y = rate of flow per unit of catchment area (Q/A) (Q = the volumetric rate of flow in the river; A = the area of the catchment)

y_0 = value of y at the (arbitrarily) chosen reference of time (i.e. t = 0)

K = characteristic time scale of the catchment drainage process (commonly referred to as the storage coefficient).

Conservation of mass requires that storage is related to outflow by the following integral, with the assumption that there is no rainfall/inflow to the catchment over the integration period:

$$S = -\int_t^\infty y\,dt \qquad (2)$$

We are currently investigating ways to apply this 'conceptual model' of groundwater storage to the uplands catchments of the Murrumbidgee. Brutsaert (2008) uses a long-term trend in 'low flow' conditions, and hence groundwater storage, as an indicator of the effects of climatic variation on groundwater storage. This may be a useful indicator for water resource assessment.

Input data

The input data required for this analysis include the long-term streamflow data along with concurrent groundwater level data.

Method 5: MODFLOW

MODFLOW, a three-dimensional (3D) finite-difference groundwater flow model (MacDonald and Harbaugh, 1988), solves the following partial differential equation describing the 3D movement of groundwater of constant density through porous material:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-W=S_s\frac{\partial h}{\partial t} \quad (4)$$

Where;

K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity

h is the potentiometric head

W is a volumetric flux per unit volume and represents sources and/or sinks of water

S_s is the specific storage of the porous material

T is time.

The groundwater storage is estimated as part of the mass balance (volumetric budget) calculations. The model requires specification of dimensionless storage coefficient values in each layer of the model. In the case of a confined and unconfined layers, these storage coefficient values are given by the specific storage and specific yield of the cell material.

The mass balance is typically produced for the modelled region, but estimations for predefined sub-regions can be made by using the ZONEBUDGET program (Haraugh, 1990).

Input data

The input data required for the storage estimation are boundary conditions, hydraulic conductivity, specific yield, storage coefficient, porosity, and aquifer top and bottom elevations.

G.2.4 Method evaluation

An assessment of the various methods for estimating groundwater storage is presented in the main text.

G.3 Regional groundwater flow

G.3.1 Definition and discussion of what is required

Groundwater flow can be considered to be regional when it occurs from an area where the groundwater is recharged to a distant location where groundwater discharges. For the purposes of the Bureau's water balance framework, the term regional groundwater flow is used to describe the movement of groundwater into and out of an area of interest, such as an aquifer or surface water drainage catchment or sub-catchment, including flow within both shallow and deeper aquifers.

Groundwater flow (Q) is calculated by using Darcy's Law:

$$Q = -k \times dh/dl \times A \quad (1)$$

where k is the hydraulic conductivity, dh/dl is the hydraulic gradient and A is the area.

G.3.2 Alternative methods

Method 1: Simple GIS calculations

If spatial data are available, groundwater flow can be calculated on the basis of Darcy's Law using a GIS. The difficulty is in relating the groundwater flow to the boundaries for the area of interest, which is essential for estimating inflows to and outflows from the area. One solution is to estimate groundwater flow across a series of line segments that make a boundary (Figure 28). The results can then by averaged or totalled along the boundary. This approach could be automated by using ArcGIS Model Builder.

The data required to calculate groundwater flow using a GIS-based approach are:

- discretisation to allow for topographic discontinuities, such as ridges and cliffs
- drainage enforcement to automatically remove spurious sinks
- error diagnostics, including identification of remaining spurious sinks and large residual error between output grid and input point data
- nugget: discontinuity at the origin that represents the effects of measurement errors or sources of variation in measurement at distances smaller than the sampling interval
- range: distance at which the semivariogram reaches an asymptote, indicating the largest distance at which data are spatially auto-correlated
- sill: height the semivariogram reaches when it asymptotes
- partial sill: sill minus the nugget
- simple kriging (Bogaert, 1996)
- ordinary kriging (Bogaert, 1996)
- universal kriging (Aboufirassi and Mariño, 1983; Gundogdu and Guney, 2007; Shamsudduha et al., 2009)
- co-kriging (Hoeksema et al., 1989; Boezio et al., 2006; Ahmadi and Sedghamiz, 2008)
- kriging with external drift (Desbarats et al., 2002; Rivest et al., 2008)
- aquifer boundaries
- aquifer geometry (i.e. thickness and elevation of top and base of aquifer)
- aquifer properties (i.e. porosity, specific yield and storage coefficient)
- elevation of watertable or potentiometric surface
- Groundwater Management Units
- groundwater levels and, from these, a potentiometric surface for each aquifer
- hydraulic conductivity
- saturated thickness

- aquifer area.

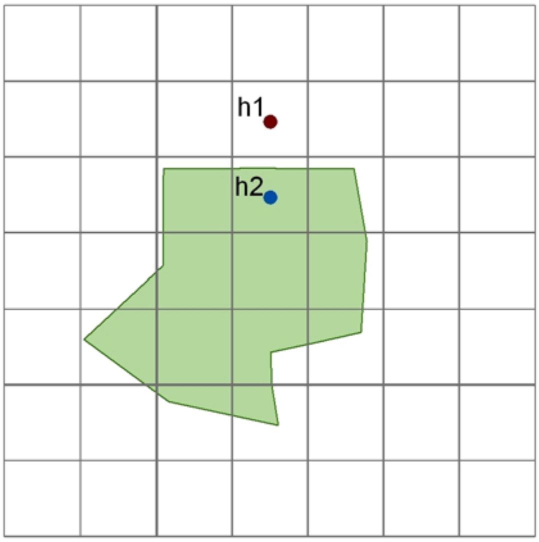

Figure 28. Simple GIS method for estimating groundwater flow into and out of an example of a subcatchment (shown in green)

Method 2: MODFLOW

MODFLOW is the most common code for predicting groundwater flow and is described in more detail elsewhere (McDonald and Harbaugh 1988). The Zone Budget package is the module used to estimate subregional water budgets for MODFLOW models (Harbaugh 1990). MODFLOW and Zone Budget would be useful for estimating groundwater flow in high-priority aquifers where groundwater flow models have already been created. They are unlikely to be used in low-priority or data-poor regions.

G.3.3 Method evaluation

The suitability of the above methods for estimating groundwater flow has been assessed in the main report. A simple GIS approach should be used in the first instance and automated by using ArcGIS Model Builder. For high-priority aquifers with existing groundwater models, the WRA section could liaise with the relevant agencies to gain access to existing groundwater models or the results from these models. It would be particularly useful to compare the modelled outputs with the results obtained using the simple GIS approach.

G.4 Groundwater recharge

Considering the definition of recharge, many terms are used in the literature to describe water movement below the root zone (such as drainage, net infiltration or percolation), and these fluxes are often equated to groundwater recharge. However, in the assessment of water resources we propose to differentiate between water draining below a root zone that may or may not reach the watertable *(potential* recharge) and water that has become part of a more connected groundwater resource below the watertable (*actual* recharge) (Rushton, 1997; Petheram et al., 2000).

G.4.1 Potential recharge

Potential recharge is usually estimated from surface water and unsaturated zone studies. It refers either to water that may and may not reach the watertable because of unsaturated zone processes, or to the saturated zone that is able to accept recharge (Scanlon et al., 2002). In this section, a review of large-scale numerical models widely used in Australia to calculate potential recharge is carried out.

WAVES

WAVES is designed to simulate energy, water, carbon, and solute balances of a one-dimensional soil–canopy–atmosphere system (Dawes and Short, 1993; Zhang and You, 1996). It is a process-based model, and it integrates soil, canopy–atmosphere with a consistent level of process detail. WAVES predicts the dynamic interactions and feedbacks between the processes.

WAVES can model the following processes on a daily time-step:

- interception of rainfall and light by canopy
- surface energy balance
- carbon balance and plant growth
- soil evaporation and canopy evapotranspiration
- surface runoff and infiltration
- saturated/unsaturated soil moisture dynamics (soil water content with depth)
- drainage (recharge)
- solute transport of salt (NaCl)
- watertable interactions.

Figure 29 shows the components of WAVES. The model is based on five balances (Zhang and Dawes, 1998):

- Energy Balance: partitions available energy into canopy and soil for plant growth and evapotranspiration (Beer’s law).
- Water Balance: handles infiltration, runoff, evapotranspiration (Penman–Monteith equation), soil moisture redistribution (Richards equation), drainage, and water table interactions.
- Carbon Balance: calculates carbon assimilation using IRM and dynamically allocates carbon to leaves, stems, and roots; also used to estimate canopy resistance for plant transpiration.
- Solute Balance: estimates conservative solute transport within the soil column and the impact of salinity on plants (osmotic effect only).
- Balance of complexity, usefulness, and accuracy.

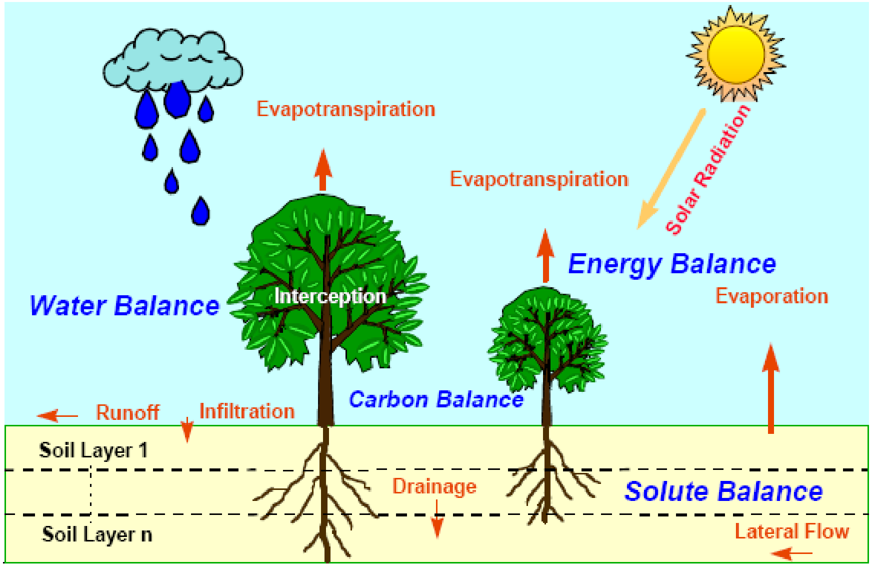

Figure 29. Conceptual diagram showing the major processes modelled by WAVES (Zhang and Dawes, 1998).

AWAP

Described in Appendix B and other parts of the text.

G.4.2 Actual recharge

In this section a review of some physical and chemical methods that assess *actual recharge* (Scanlon et al., 2002) to groundwater will be presented. The following techniques can be used to evaluate large-scale recharge estimates in order to provide improved water budget analyses.

Watertable fluctuation method

The watertable fluctuation method (WTF) can be used to estimate recharge rates in the study area. The method assumes that rising groundwater levels in an unconfined aquifer are the result of recharge water arriving at the watertable; the net subsurface flow is balanced by flow away from the bore (Healy and Cook, 2002). Therefore, the WTF method can be applied only to bores at or very close to the watertable and to aquifers that show a strong, and relatively immediate, response to rainfall events. As such, recharge can be calculated as (Fetter, 1994):

$$R = S_y \, \Delta h / \Delta t \qquad (1)$$

where R is the recharge rate, S_y is the specific yield, Δh is the change in water level, and Δt is the change in time. Values of Δh can be manually estimated from antecedent recession curves fitted to hydrographs. Automated procedures for calculating Δh, such as master recession curve (MRC), and other approaches are also available (Delin et al., 2007). However, further evaluation of these procedures is needed.

For unconfined bores that show a constant increase in groundwater elevations, the increase in recharge over time can be calculated as:

$$\Delta h / \Delta t = (R_c - R_m)/S_y \qquad (2)$$

where

Δh is the change in watertable height, Δt is change in time, S_y is the specific yield of the aquifer, and ($R_c - R_m$) is the increase in recharge. Typically, in the case of an unconfined aquifer the specific yield can be assumed equal to the storativity (Fetter, 1994).

Direct measure

This method is a physical direct measure of spatially averaged recharge that can be related, for example, to a particular rainfall episode, floods or increased recharge due to irrigation or land clearing. It does require estimates of specific yield and it assumes that lateral flow rates are much slower than vertical flow rates; these assumptions limit the method's accuracy and applicability. In addition, further evaluation is required before the extrapolation of point estimates of recharge from water table fluctuations to a regional estimate of recharge could be used in the WBA model.

Type of data required

The groundwater level of a bore through time is needed for the analysis described above. This information is Water Regulations category 2a data.

Time scales

Time scales related to this methodology can vary from the duration of a particular event, such as flood or high rainfall, to the length of the hydrographic record. Therefore, it is expected that seasonal to monthly recharges will represent the shortest time scale.

Evaluation

The ease of use of the method, the availability of the data required, and the possibility of using automated procedures both for spatial extrapolation and for hydrograph analysis make the method a candidate for the Australia-wide groundwater balance analysis. The WTF method may also be useful for checking other estimates of recharge rates to groundwater, obtained by indirect techniques (often by estimating potential recharge).

Chloride mass balance

The chloride anion is an extraordinarily stable ionic species. Once introduced to natural water, it is usually advected at the same rate as water and it is not normally removed from the water by geochemical processes (Phillips, 2000).

In semi-arid areas, where runoff is negligible, chloride mass balance may be used to determine recharge rates (Allison et al., 1990; Herczeg and Edmunds, 2000; Scanlon et al., 2002; Walker et al., 2002; Leaney et al., 2003), as follows:

$$R = P\,Cl_{ppt} / Cl_{gw} \tag{3}$$

where R is groundwater recharge and Cl_{ppt} and Cl_{gw} are the chloride concentrations in precipitation and groundwater, respectively. To use this method, all Cl has to be derived from the evapotranspiration of rainfall. Cl/Br ratios provide a test of this assumption (Cartwright et al., 2007).

Direct measure

This is a chemical method that uses an environmental tracer is a direct measure of local recharge to groundwater; however, depending on the groundwater flow, it can integrate recharge from areas upgradient of the measurement point. Further

investigation is required into the possibility of large-scale extrapolation of the results obtained by this method.

Type of data required

Major ion analyses of groundwater and rainfall are required for this methodology. Chemical analyses are not part of the Water Regulations data. However, many bores throughout Australia have been sampled and major ion chemistry information is available. CSIRO is also undertaking chemical analysis of rainfall through Australia. If possible, Water Regulations data should be modified to include major ion chemistry. This can yield important information on QA/QC assessment on the chemical analysis and data on Cl concentration.

Time scale

The time scale related to this methodology ranges from years to thousands of years.

Evaluation

The ease of use of the method and the possibility of using automated procedures for spatial extrapolation makes it a very good candidate for the Australia-wide WBA. However, groundwater quality data other than those prescribed in Water Regulation 9b are required. The need for major ion chemistry versus the Australian-wide availability of this data should be very carefully considered.

This technique may also be used to validate potential recharge rates to groundwater obtained by indirect techniques.

Stable isotopes

$\delta^{18}O$ and $\delta^{2}H$ are considered ideal tracers of water movement, since they form the water molecule itself. Stable isotopes behave differently in physical and chemical processes because of a difference in mass. For example, during evaporation and rainout from the atmosphere, $\delta^{18}O$ and $\delta^{2}H$ fractionates (Clark and Fritz, 1997). The resulting variation in isotopic concentration can give information on the climate at the point of infiltration and also on the origin of water mixing between aquifers and on discharge processes. It can also provide an indication of the past recharge climatic condition (Coplen et al., 2000).

The difference in stable isotope signature of rivers and local precipitation (Local Meteoric Water Line) can be used to assess groundwater recharge. In general, $\delta^{18}O$ and $\delta^{2}H$ provide good information on recharge sources; however, it is generally difficult to quantify recharge rates (Scanlon et al., 2002).

Direct measure

This is a chemical method that uses environmental isotopes to measure direct recharge to groundwater. To assess recharge rates by this method a thorough understanding of recharge processes in the study area is needed.

Type of data required

Stable isotope analysis.

Time scale

The time scale ranges from seasonal in areas of high flux to hundreds of years in areas of low flux.

Evaluation

This method requires data additional to those required by the Water Regulation (9b category) and a comparison between surface water, rainfall (specifically the knowledge of the LMWL), and groundwater stable isotope ratios. Furthermore, it is not always possible to gain quantitative, rather than qualitative, information on recharge rates throughout Australia.

Groundwater dating

Radioactive (e.g. ^{14}C, ^{36}Cl) and event marker (e.g. ^{3}H, CFCs) tracers have been used successfully in various part of Australia to calculate actual recharge to groundwater (Bird et al., 1989; Cresswell et al., 1999; Dogramaci and Herczeg, 2002; Harrington et al., 2002; Cartwright and Weaver, 2005; Cartwright et al., 2007). Horizontal or vertical flow velocity within an aquifer can be estimated by using radioactive decay or event marker tracer concentration in rainfall compared with that of groundwater. Groundwater velocity (v) coupled with effective porosity (n_e) can be used to constrain fluxes and hence recharge (R) to a confined aquifer with lateral flow, as follows (Zhu and Murphy, 2000; Healy and Cook, 2002):

$$R = v\ n_e\ H/L \quad (4)$$

where

H is the thickness of the confined aquifer and L is the estimated length of the recharge zone.

For unconfined aquifers dominated by vertical piston flow, vertical recharge to groundwater can be calculated as follows (Cook and Bohlke, 2000):

$$R = v\ n_e \quad (5)$$

^{14}C

Radiometric carbon dating is a powerful tool for investigating long-term groundwater flow directions on the basis of the consistency of groundwater ages along possible flow paths, because it provides groundwater travel times that can be used to calculate groundwater velocities, hydraulic conductivities and/or effective porosity (Edmunds and Smedley, 2000; Zhu and Murphy, 2000). Harrington et al. (2002) showed that the combined use of ^{14}C dating and Cl mass balance is very effective for estimating long-term groundwater recharge in the arid areas of central Australia.

However, for ^{14}C data to be meaningful, the dilution of cosmogenic ^{14}C with ^{14}C-free dissolved inorganic carbon (DIC) and the extent of groundwater mixing should be considered. Both of these processes may yield apparent groundwater ages that do not reflect real groundwater travel time (Dogramaci and Herczeg, 2002; Gonfiantini and Zuppi, 2003).

^{36}Cl

Chlorine 36 has many advantages as a dating tool for very old groundwater. These advantages include a suitable half-life of 301 ± 4 ka, simple geochemistry, conservative behaviour in groundwater, and a general absence of subsurface sources at levels comparable to the atmospheric input. Elevated $^{36}Cl/Cl$ ratios have been attributed to nuclear weapons testing (Davis et al., 2001).

^{36}Cl activity in groundwater depends primarily upon the long-term atmospheric fallout of ^{36}Cl and the subsequent incorporation of ^{36}Cl into precipitation and recharge to groundwater. Groundwater residence times are calculated with reference to the local input ratio, determined as the normal average of values for modern samples. Use of ^{36}Cl as a groundwater dating tool or tracer has previously been reported in a number of Australian studies (Cresswell et al., 1999; Davie et al., 1989; Love et al., 2000; Mazor, 1992; Lehmann et al., 2003).

Limitations to this technique include uncertainties associated with (a) constraining the input $^{36}Cl/Cl$ ratio, (b) the accurate determination of secular (in situ) equilibrium (in the deep subsurface), (c) the introduction of chloride from local salts or crustal fluids, and (d) mixing between groundwater masses (Kulongoski et al., 2008).

^{3}H and $^{3}H/^{3}He$

Tritium is a short-lived isotope with a half-life of 12.43 years. Typically, recharge estimates using ^{3}H rely on determining the velocity of elevated bomb pulse concentrations produced in the 1950s and 1960s by atmospheric nuclear testing. Tritium has been used widely in the past; however, bomb pulse concentrations have been greatly reduced as a result of radioactive decay. In the Southern Hemisphere, where ^{3}H concentrations are an order of magnitude less than in the northern one, current ^{3}H levels of the bomb pulse water approach those of modern precipitation.

The use of ^{3}H to date groundwater has been replaced by the use of tracers such as CFCs and ^{3}H and $^{3}H/^{3}He$. Dispersive mixing can result in ±50% uncertainty in $^{3}H/^{3}He$ ages prior to 1970 (Scanlon et al., 2002).

CFCs

Chlorofluorocarbons (CFCs) have been introduced in the atmosphere and hydrosphere during the last couple of decades. The steady increase in CFC levels has been used for dating young groundwater. The first appearance of CFCs and $^{3}H/^{3}He$ can be used to estimate recharge rates where groundwater flow is approximated to a vertical piston flow (Scanlon et al., 2002). However, the temperature dependent solubility transport through the unsaturated zone plays an important role. In fact, it appears that CFC-11 is readily degraded under anoxic conditions, whereas CFC-12 degrades about 10 times more slowly and CFC-13 is adsorbed to sediment particles (Appelo and Postma, 2005).

Direct measure

These are chemical methods that use different groundwater-dating methodologies to measure direct recharge to groundwater. To assess recharge rates by these methods a thorough understanding of groundwater flow, inter--aquifer mixing and groundwater rock interaction in the study area is needed.

Type of data required

Isotope (^{14}C, ^{36}Cl, ^{3}H, $^{3}H/^{3}He$) and CFC concentrations of groundwater.

Time scale

The time scales range:

- for ^{14}C, from modern up to 30,000 years
- for ^{36}Cl, up to 2 million years

- for ^{3}H, $^{3}H/^{3}He$ and CFCs, up to 50 years.

Evaluation

These methods require data additional to those required by the Water Regulation (9b category). Usually, analyses for this type of data are expensive, and therefore the availability of these data is restricted to small, well studied areas. It is unlikely that any of these methods can be used in an Australian-wide WBA. Where previous studies are available, however, large-scale recharge rate can be evaluated independently by using recharge rates obtained by these methods.

Table 21. Assessment of actual recharge methods against data availability and spatial and temporal scale criteria

Method	Data availability	Spatial scale	Temporal scale	Recommendations
WTF	Regulations data (category 2a)	From local to subregional	From event scale to length of records	Review automated methods for calculations and large-scale grid extrapolation
Cl mass balance	Data not available	From local to regional	From years to thousands of years	Assess possibility of obtaining data and using the method Australia-wide
$\delta^{18}O$ & $\delta^{2}H$	Data not available	From local to regional	From seasonal to hundreds of years	Where prior study information is available, use data to compare potential recharge rates
^{14}C	Data not available	From local to regional	Up to 30,000 years	Where prior study information is available, use data to compare potential recharge rates
^{36}Cl	Data not available	From local to regional	Up to 2 Ma	Where prior study information is available, use data to compare potential recharge rates
^{3}H & $^{3}H/^{3}He$	Data not available	From local to regional	Up to 50 years	Where prior study information is available, use data to compare potential recharge rates
CFCs	Data not available	From local to regional	Up to 50 years	Where prior study information is available, use data to compare potential recharge rates

Recommendation:

It is recommended that WAVES is used to calculated groundwater recharge and the other methods are used as a comparison, depending on data availability. Further information on the recommendation is given in the main text of this report.

G.5 Interaction between Groundwater and Surface water stores

G.5.1 River–groundwater interaction models being developed in eWater

Rassam and Werner (2008) provide a review of processes that are important to groundwater –surface water interaction. A number of numerical models are also evaluated for their representation of these processes (e.g. FLOWNET, CAPZONE, GFLOW, WinFLOW, HYDRUS-2D, MODFLOW, FEFLOW, MODBRANCH, SWAT/MODFLOW, FEFLOW.MIKE 11, GSFLOW, MODHMS, MIKE SHE, HydroGeoSphere).

The review by Rassam and Werner (2008) is part of an eWater project that is currently developing three different models for representation of groundwater – surface water interaction that reflect the nature of the interaction in three different river valley environments (in uplands and mid-reaches and within river floodplains or trenches). These models aim to provide a simple, yet realistic, representation of river – groundwater interaction for the environments most prevalent in Australia. It is hoped that these models or prototypes may be available for review by the Bureau in the near future.

G.5.2 'Connectivity Mapping' approach developed for Murray-Darling Basin Sustainable Yields

Surface water – groundwater connectivity mapping involves determining the direction and magnitude of groundwater flux to or from streams and rivers (Parsons et al., 2008). The approach uses Darcy's Law, and hence estimates of hydraulic conductivity and groundwater gradients need to be available. River and groundwater levels are compared at a single point in time to provide a snapshot of the direction and magnitude of the flow between surface water and groundwater. This approach has been used in MDBSY Project. Some of the advantages of connectivity maps are that they:

- provide an alternative approach to the numerical models
- serve as a check of the surface water modelling and groundwater modelling components of the project
- provide an initial indication that can be used as the basis for more detailed conceptualisation as part of modelling
- are a powerful visual aid.

Input data

The input data required for this mapping process include stream and groundwater levels (bore-data) and estimates of hydraulic conductivity.

G.5.3 Q-Lag (Brodie et al., 2007)

This method involves comparing daily streamflow percentiles derived from the gauging station record with daily rainfall from a representative climate station within the catchment. By taking a frequency analysis approach, the streamflow and rainfall data are compared at different percentiles. Three case studies have been examined, namely: Wilsons River, NSW (a gaining stream); Ovens River, Victoria (a dominantly gaining river); and Mooki River, NSW (a losing stream).

Q-Lag analysis has the potential to derive additional information about stream–aquifer connectivity that remains hidden from more conventional hydrographic analysis.

This approach appears to offer a data-based method that uses streamflow to estimate the groundwater–river interaction. Although a full evaluation has not been possible in this review, it may be useful to consider this approach further in a pilot study.

For more information

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