NSW General Purpose Water Accounting Reports

Groundwater Methodologies
Foreword

Following the intergovernmental agreement on the National Water Initiative, the Water Accounting Standards Board (WASB), which operates as an independent advisory board to the Bureau of Meteorology (BoM) was formed with the task of implementing a national standard for water accounting. This process has resulted in the production of the ‘Australian Water Accounting Standard 1 (AWAS 1)’ which defines the structure for preparing a ‘General Purpose Water Accounting Report (GPWAR)’.

The NSW Office of Water are adopting AWAS 1 and publish annual GPWAR’s for NSW Murray Darling Basin catchments that provide detailed information of the resource situation and water resource management that occurred within the reporting year. The scope of this reporting is intended to broaden over time.

Groundwater is not only an important source of water that meets a wide range of purposes across NSW, but also forms a significant component of the surface water balance for many catchments. As such the GPWAR’s for the inland regulated surface water catchments will also contain integrated information relating to the groundwater balance.

While the level of detail in these GPWAR's will be significantly less to that of the surface water component, in the longer term it is envisaged that further to the GPWAR’s being published in line the surface water catchment boundaries, GPWARs will be produced that are tailored for groundwater management, both aligning the groundwater management areas and containing detailed information on the management of the groundwater management areas.

The NSW Office of Water found that groundwater data suitable for inclusion in an annual accounting product is highly variable in extent. For many of the inland alluviums that are associated with relatively high levels of entitlement, reasonable coverage of monitoring bores and metered extraction data, a computer simulation model is available for the area, and once updated with the required input data, can supply all of the requirements to produce a water balance of the aquifer. For all the other areas however, little or no data is readily available to provide an estimate of the annual groundwater budget for the area.

In order to provide a greater coverage of groundwater data in the water accounts NOW obtained funding under the federal modernisation and extension of hydrologic monitoring systems program to develop and implement groundwater methodologies for water accounting. This document details those methodologies that were developed and that are actively being applied in the production of the NSW Office of Water GPWARs
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### Abbreviations

<table>
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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AET</td>
<td>Actual Evapotranspiration</td>
</tr>
<tr>
<td>AHD</td>
<td>Australian height datum</td>
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<tr>
<td>AWAS</td>
<td>Australian Water Accounting Standard</td>
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<td>AWC</td>
<td>Available Water Capacity</td>
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<td>BoM</td>
<td>Bureau of Meteorology</td>
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<tr>
<td>CN</td>
<td>Runoff Curve Number</td>
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<td>ED AWAS 1</td>
<td>Exposure Draft of Australian Water Accounting Standard 1</td>
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<tr>
<td>ET</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
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<td>GPWAR</td>
<td>General Purpose Water Accounting Report</td>
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<tr>
<td>MODFLOW</td>
<td>Modular Three-Dimensional Finite-Difference Groundwater Flow Mode</td>
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<tr>
<td>NOW</td>
<td>NSW Office of Water</td>
</tr>
<tr>
<td>P</td>
<td>Precipitation</td>
</tr>
<tr>
<td>PET</td>
<td>Potential Evapotranspiration</td>
</tr>
<tr>
<td>RF</td>
<td>Irrigation return flow</td>
</tr>
<tr>
<td>SCS</td>
<td>Soil Conservation Service</td>
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<tr>
<td>SILO</td>
<td>Specialized Information for Land Owners climate database</td>
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<tr>
<td>SW</td>
<td>Soil Water</td>
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<td>SWB</td>
<td>Soil Water Budget</td>
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<tr>
<td>T-M</td>
<td>Thornthwaite-Mather</td>
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<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
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<td>WASB</td>
<td>Water Accounting Standards Board</td>
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<td>WTF</td>
<td>Water Table Fluctuation</td>
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Introduction

To provide groundwater budget information across the full extent of the reporting area for a GPWAR it was necessary to implement and utilise various groundwater methodologies. The confidence in the groundwater budget estimates produced and the number of parameters within the groundwater budget that can be estimated varies significantly with each method.

The method implemented for any given area is determined according to Figure 1. This report provides a brief generalised description of the groundwater model used in producing groundwater components for a GPWAR (‘Method A’), and detailed information on the other two methodologies that were developed for areas that do not have groundwater model coverage (‘Method B’ and ‘Method C’).

Figure 1: Groundwater methodology decision tree
Groundwater methodologies

The groundwater methodologies that are used to obtain the groundwater budget components reported in GPWAR reports are discussed in the subsequent sections.

Method A – Groundwater Models

NSW has 90% of its groundwater usage in the ‘Big Six’ groundwater areas (Gwydir downstream of Pallamallawa, Upper and Lower Namoi, Macquarie downstream of Narromine, Lachlan downstream of Lake Brewster, Murrumbidgee downstream of Narrandera and the Murray downstream of Corowa) and smaller high use alluvial aquifers associated with the Border Rivers, Mid Macquarie (Narromine to Wellington), Upper Lachlan (Lake Cargelligo to Cowra), Mid Murrumbidgee (Narrandera to Tarcutta Creek), Botany, Upper Murray (Albury to Corowa).

The NSW Office of Water (NOW) has developed a series of groundwater models for these areas using the groundwater flow simulation computer program MODFLOW. There are also several other models currently under development.

MODFLOW is a three-dimensional finite-difference groundwater flow model that was developed by the United States Geological Survey (USGS) and is the most widely used program in the world for simulating groundwater flow. It has a modular structure that allows it to be easily modified to adapt the code for a particular application.

MODFLOW is used to simulate steady and non steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. The main hydrological processes simulated by the model are recharge, groundwater pumping, groundwater flow to drains, evapotranspiration, lateral flows, and interaction between the shallow groundwater system and the river system.

Method outputs available for use in the GPWARs

The following parameters of the water budget are extracted from modflow and available for use in the annual General Purpose Water Accounting Reports (GPWARs) published by NOW

- Lateral flow
- Recharge (rainfall and irrigation)
- Aquifer inflow from river
- Aquifer outflow to river
- Evapotranspiration – from top layer of aquifer
- Usage
- Change in Storage

With this a full water budget is able to be achieved and reported, with the only parameter required to be estimated in order to report in line with the AWAS1 being the extractable volume available at the start of the year being reported.

Limitations

While the groundwater models are useful tools for supporting the water accounting products, the models are not currently being specifically calibrated to the observed groundwater levels that occurred within the reporting period of the GPWARs. The models are being updated and the input data fine tuned to the reporting period of the GPWARs, however the original model calibration, which is based on a longer term historic period is assumed to be valid for the reporting period of the GPWAR.

Method B – Water Table Fluctuation (WTF)

Background

The water-table fluctuation method provides an estimate of groundwater recharge by analysis of water-level fluctuations in groundwater monitoring wells and is based on the assumption that a rise in water-table elevation measured in monitoring wells is caused by the addition of recharge
Across the water table, lateral inflows or inter-layer leakage. As the water level measured in an observation well is representative of an area of at least several tens of square metres, the WTF method can be viewed as an integrated approach and less of a point measurement than those methods that are based on data in the unsaturated zone (Cook et al, 2002). Techniques based on groundwater level changes are amongst the most widely applied techniques in groundwater recharge rate estimates. This is most likely due to the abundance of water level data from observation bores and the simplicity of applying the method to estimate the recharge from temporal water level data (Cook and Healey, 2002).

The WTF method links the change in groundwater storage over time with resulting groundwater fluctuation from monitoring data, through the specific yield of the unconfined aquifer which is represented by equation 2.

\[ \Delta S = A \Delta h S_y \]  \hspace{1cm} \text{(Equation 1)}

Where:
- \( \Delta S \) is change in groundwater storage in a defined time interval (e.g. \( t_0 \) to \( t \)) (m³);
- \( A \) is the surface area of the aquifer (m²);
- \( \Delta h \) is water level rise in observation wells at a defined time interval (e.g. \( t_0 \) to \( t \)) (m); and
- \( S_y \) is the specific yield of the aquifer.

**Groundwater budget**

The water budget (or balance) of a groundwater system can be determined by calculating the inputs and outputs of water, and the storage changes of the groundwater system. The major inputs of water are from rainfall, irrigation return flow and seepage from rivers. The major outputs from a groundwater system are evapotranspiration, baseflow to rivers and groundwater pumping.

Changes in groundwater storage can be attributed to the difference between inflows and outflows of water over a defined time interval. The storage change can be expressed as:

**Change in storage (\( \Delta S \)) = inflows - outflows**

Expanding this, the water budget equation with all the relevant inflow and outflow components, can be mathematically expressed as follows:

\[ R_{\text{rain}} + RF + Q_{\text{on}} + Q_{\text{river}} = ET + PG + Q_{\text{off}} + Q_{\text{bf}} + \Delta S \]  \hspace{1cm} \text{(Equation 2)}

Where:
- \( R_{\text{rain}} \) is direct recharge from rainfall (m³);
- \( RF \) is irrigation return flow (m³);
- \( Q_{\text{on}} \) and \( Q_{\text{off}} \) are lateral groundwater flows into and out of the groundwater system (m³);
- \( Q_{\text{river}} \) is river seepage recharge (m³);
- \( ET \) is evapotranspiration (m³);
- \( PG \) is extraction of groundwater by pumping (m³);
- \( Q_{\text{bf}} \) is baseflow (groundwater discharge to streams or springs) (m³); and
- \( \Delta S \) is change in groundwater storage (m³).

A positive \( \Delta S \) indicates an increase in groundwater storage volume, while a negative \( \Delta S \) represents a decrease in groundwater storage volume. The different components of the groundwater budget are schematically shown in Figure 2.
**NOW Application of the Water Table Fluctuation Method**

In areas deemed applicable NOW is adopting a combination of the groundwater water budget and the Water Table Fluctuation (WTF) method for calculating the groundwater budget components for annual GPWAR’s (note the total groundwater extent of each GPWAR may be made up of multiple methods).

The fundamental unknown parameter in applying the WTF method is the specific yield. There are several methods for determining Sy including laboratory methods, field pumping test methods, volume balance methods and water budget methods. For the purposes of producing annual accounting figures, however many of these methods are either far too resource intensive to apply or limited by data availability.

Previous studies have highlighted that seasonality can be utilised to derive the specific yield for a target area. To estimate the specific yield and groundwater recharge in a semi-arid basin, Mere’chal et al. (2006) employed the split use of the combination of the water fluctuation method with water budget equation, whereby the hydrologic year was separated into two extended seasons of recharge (wet period) and no recharge (dry period) with accompanying changes in water table, first to estimate the specific yield from the water table drop during the dry period (no recharge) and, second, to estimate recharge from the water table rise during the wet period, after considering all other water budget components explicitly.

Inland NSW catchments have a seasonal climate and groundwater level fluctuation often has a distinct seasonality. For the application of this method it was assumed that groundwater levels in many aquifers can be divided into two periods of recharge (wet period) and negligible recharge (dry period).

In using the WTF method for water accounting NOW are attempting to derive the specific yield through utilising the climate seasonality of the aquifer and with this define the water budget for a specific time interval. While this has its limitations, the efficiency and the specific requirement in which the method can be applied is highly beneficial for producing annual water accounting figures.

Applying the Water Table Fluctuation method therefore involved the following steps:

- Define a wet and dry period;
• Estimate the water level change (Δh);
• Calculate the Specific Yield using the defined dry period; and
• Calculate recharge in the wet period using the specific yield calculated in previous step and water level rise.

**Defining the wet and dry period**

When using the combination of groundwater budget equation with WTF method to calculate the specific yield and the annual recharge, the most basic requirements are that the aquifer should be unconfined and that wet and dry periods are well differentiated (e.g. there are significant groundwater rises and decline). A graph showing hypothetical wet and dry periods for the study area is shown in Figure 3.

In Figure 3 the dry period is the period of groundwater decline and the wet period is the period of rising groundwater level. The steps for creating the graph shown in Figure 3 are:

- Obtain the monthly water levels for the monitoring bores in the study area;
- Create a monthly water levels contour map for the study area;
- Calculate the monthly average water level from the monthly contour maps;
- Create a monthly water levels graph, such as the one shown in Figure 3, using the average monthly water levels calculated in previous step.

![Figure 3: Idealised well hydrograph in the study area with seasonal water table fluctuations](image)

**Estimating the water level change (Δh)**

There are three water level changes that are employed in the WTF method, which are:

- The water level rise during the wet period (Δh\text{wet}), which is estimated as the difference between the peak of a water rise and the lowest level that the water levels had reached before it started to rise. This estimate generally relies on the assumption that there will be one distinct rise during the wet period from recharge, and only minor fluctuations as a result of other components of the budget;
The water level drop during the dry period \( (\Delta h_{\text{dry}}) \), which is how much the water levels dropped during the dry period, it is estimated as the difference between water levels at beginning and the end of the dry period; and

- Annual groundwater level change \( (\Delta h_{\text{annual}}) \) which is the change in water levels over a 12 month period (for example; water level change between July 1, 2006 and July 30, 2007).

**Calculate Specific Yield using the defined dry period \( (S_y) \)**

The specific yield is defined as the quantity of water that a unit area of saturated permeable rock or soil will yield when drained by gravity. Specific yield may be expressed as a ratio or as a percentage by volume.

\[
S_y = \frac{\Delta S}{A\Delta h};
\]

(Equation 3)

where:

- \( S_y \) is specific yield;
- \( \Delta h \) is the water levels change;
- \( \Delta S \) is change in storage; and
- \( A \) is the surface area of the aquifer

Combining the water budget equation (1) with equation (2), we obtain:

\[
R_{\text{rain}} + RF + Q_{\text{on}} + Q_{\text{river}} = ET + PG + Q_{\text{off}} + Q_{bf} + AS_y \Delta h
\]

(Equation 4)

By applying equation (4) to the dry period, during which \( R_{\text{rain}} = 0 \), we obtain the following equation:

\[
RF_{\text{dry}} + Q_{\text{river}}^{\text{dry}} + Q_{\text{on}}^{\text{dry}} = PG^{\text{dry}} + ET^{\text{dry}} + Q_{bf}^{\text{dry}} + Q_{off}^{\text{dry}} + AS_y \Delta h^{\text{dry}}
\]

(Equation 5)

With the exception of specific yield, all the other components in equation (5) can be estimated and the specific yield is the only unknown parameter in the equation. Rearranging equation (5) and solving it for \( S_y \), we can obtain:

\[
S_y = \frac{(RF_{\text{dry}} + Q_{\text{river}}^{\text{dry}} + Q_{\text{on}}^{\text{dry}}) - (PG^{\text{dry}} + ET^{\text{dry}} + Q_{bf}^{\text{dry}} + Q_{off}^{\text{dry}})}{A\Delta h^{\text{dry}}}
\]

(Equation 6)

where, the dry superscript indicates the dry period component of the groundwater budget equation.

**Calculate Recharge in the wet period**

During the wet period, the water budget equation (1) can be written as:

\[
R_{\text{rain}} + RF_{\text{wet}} + Q_{\text{river}}^{\text{wet}} + Q_{\text{on}}^{\text{wet}} = ET_{\text{wet}} + Q_{bf}^{\text{wet}} + Q_{off}^{\text{wet}} + AS_y \Delta h^{\text{wet}}
\]

(Equation 7)

The rain recharge as a residual volume can then be calculated by removing the contribution of other recharge components according to the following equation:

\[
R_{\text{rain}} = \left( A \times S_y \times \Delta h^{\text{wet}} + PG^{\text{wet}} + ET_{\text{wet}} + Q_{bf}^{\text{wet}} + Q_{off}^{\text{wet}} \right) - \left( RF_{\text{wet}} + Q_{\text{on}}^{\text{wet}} + Q_{\text{river}}^{\text{wet}} \right)
\]

(Equation 8)

All components of equation 8 have been previously defined. The “wet” superscript stands for the wet period groundwater budget components.

**Method outputs for use in the GPWARs**

The following parameters of the water budget are produced by the WTF method and available for use in the NSW Office of Water GPWAR’s
• Aquifer loss to river
• Aquifer gain from river
• Pumping
• Recharge (irrigation and rainfall)
• Evapotranspiration
• Leakage between the different groundwater systems

Usage for the area can be extracted from NOW’s Water Accounting System or estimated for areas with no metering systems in place. As such a full water budget is able to be achieved and reported, with the only parameter required to be estimated in order to report in line with the proposed water accounting standard being the extractable volume available at the start of the year being reported.

Limitations
The main limitations of the WTF technique are:

• The method requires a specific yield, which is representative of the whole aquifer to be calculated;
• The observation wells should be located such that the monitored water levels are representative of the area as a whole;
• The method cannot account for a steady rate of recharge, where the rate of recharge is constant and equal to the rate of drainage away from the water table.

Method C – Soil Water Budget (SWB)

Background
The Soil Water Budget (SWB) approach is a recharge estimation method that is based on the water balance in the soil-water zone. The soil-water zone extends from the ground surface to the depth that plant roots normally reach. The method distributes water from precipitation between surface runoff, evapotranspiration and the volume that enters the ground. Some of the water that enters into the ground binds to the mineral grains of the soil and is later taken up by plant roots, while the remaining volume drains under force of gravity and becomes a recharge to the groundwater. It is this recharge that this method is mainly concerned with and attempts to quantify.

Recharge water that is calculated by this method still has to go through the immediate unsaturated zone before it reaches the water table. Some of the water may be lost to evaporation or become an interflow in the unsaturated zone before it finally reaches the water table. Therefore, unless the water table is at shallow depth, the recharge calculated by this method is an estimate of the potential recharge as opposed to the actual recharge.

Soil-water budget models have historically been used as a means to examine the relationship between various components of the hydrologic cycle (for example, precipitation, evapotranspiration, runoff and groundwater recharge). Among the current methods available to estimate the soil water budget from simple soil and climate data, the method proposed by Thornthwaite-Mather (1955) (T-M model) is one of the most widely used. This procedure allows for the estimation of the actual evapotranspiration, soil water deficit and excess as well as the potential recharge to the groundwater. Such water budget models have been used for a wide range of purposes including a global water budget (Mather, 1969; Legates and Mather, 1992; Legates and McCabe, 2005); developing climate classifications (Thornthwaite, 1948); estimating soil-moisture storage (Alley, 1984; Mintz and Serafini, 1992), estimating runoff (Alley, 1984, 1985; Yates, 1996; Wolock and McCabe, 1999), estimating irrigation demand (McCabe and Wolock, 1992); and estimating recharge (Steenhuis and Van der Molen, 1986)
The Soil Water Budget method that is documented herein uses a modified version of the Soil-Water-Balance (SWB) code that is written in Fortran 95 and was developed by the United States Geological Survey (USGS) (Westenbroek et al, 2010). The code calculates the components of water balance at a daily time step by means of a modified version of the Thornthwaite-Mather soil water balance approach (Thornthwaite, 1948; Thornthwaite-Mather 1957). The original version of the code required the program input and output data to be in imperial units. As imperial units are not used in Australia the program was modified by the NSW Office of Water to accommodate SI units.

SWB model calculates the spatial distribution of soil water budget components using a gridded data structure. Each budget component is calculated separately for each cell in the model grid. Sources and sinks of water within each cell are determined on the basis of climate data and landscape characteristics. The landscape characteristics that model uses include the landuse, soil type, vegetation type and topography. The model is essentially a book keeping technique that tracks the balance between the inflow of water from precipitation and snow melt and the outflow of water by evapotranspiration, water to soil moisture storage, surface runoff and recharge. The recharge in each grid cell is calculated as the difference between the total water inflow and total water outflow and change in cell soil moisture (eq.9).

Figure 4 shows a schematic representation of the T–M soil water budget model. Readers are referred to Westenbroek et al (2010) for a more detailed introduction of the model.

Figure 4: Schematic diagram showing T-M soil water budget model

\[\text{recharge} = (\text{precip} + \text{snowmelt} + \text{inflow}) - (\text{interception} + \text{outflow} + \text{ET}) - \Delta\text{soilmoisture}\]

\[(\text{Equation9})\]

where:

\text{recharge} is program calculated grid cell recharge
precip is precipitation. The precipitation data are input into the program as daily values either as a time series at a single station or as a series of daily Arc ASCII or Surfer grid files. The daily Arc ASCII precipitation grid files can be downloaded from the Australian Bureau of Meteorology (BoM) website.

snowmelt is the water from the melted snow. Snow is allowed to melt and/ or accumulate on a daily basis. From the daily minimum and maximum temperature, the program decides whether or not the rain falls as snow. It also, keeps track of the accumulated snow and decides when the snow melts.

inflow is the water that flows from up the gradient cells into this cell. The inflow is calculated by use of a flow-direction grid derived from a digital elevation model (DEM) to route outflow to the adjacent down gradient grid cells.

interception – is part of precipitation that is trapped by the plant canopy. A user specified amount of rainfall is assumed to be trapped by the plants.

outflow – is the surface runoff from this cell to the down gradient cells. The outflow from grid cell is calculated by use of the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) curve number rain fall runoff relationship

The curve number method is an empirical formula used for predicting direct runoff from a rainfall event in particular area. The SCS curve number runoff equation is:

\[
Q = \frac{(P - I_a)^2}{(P - I_a) + S}; \text{ where } I_a = 0.2S \text{ and } S = \left( \frac{25400}{CN} \right) - 254
\]

(Equation 10)

Where:
P is rainfall (mm);
Q is runoff (mm);
Ia is initial abstraction (mm);
S is potential maximum retention after runoff begins (mm);
CN is the runoff curve number.

The runoff is zero when the rainfall depth is less than the initial abstraction (Ia) or 0.2S.

The curve number (CN) is a parameter that relates potential maximum retention to the soil type and land cover, and is dependent on the antecedent soil moisture. The CN that corresponds to the medium soil moisture (CN(II)), which is used for the design purposes, can be obtained from published NRCS lookup tables. The CN that corresponds to the minimum (CN(I)) and maximum (CN(III)) soil moistures can be calculated according to following equations:

\[
CN(I) = \frac{CN(II)}{(2.281 - 0.01281CN(II))} \text{ and } CN(III) = \frac{CN(II)}{(0.427 + 0.00573CN(II))}
\]

(Equation 11)

ET – is evapotranspiration. The SWB code allows for any of five commonly applied estimation methods for potential evapotranspiration these being;

Thorthwaite – Mather (1957);
Jensen – Haise (1963);
Blaney – Criddle (Blaney – Criddle, 1966; Allen and Pruitt, 1986; Jensen ans others, 1990);
Turc (1961); and
Hargreaves and Samani (1985).
In the current form of the code however only Hargreaves and Samani (1985) can read temperature files in grid format.

**NOW application of the Soil Water Budget method**

NOW are applying the SWB method in groundwater areas where it is not feasible to use either of the other two methods previously documented due to data limitations. From this method NOW is obtaining an annual estimate of potential groundwater recharge for a defined area that can be incorporated in the GPWARs.

The SWB code requires the user to provide four gridded data sets: hydrologic soil groups; land use; surface-water flow direction; and available soil-water capacity. Also, the program requires tabulated for gridded precipitation and temperature files. Finally, the model requires a lookup table that assigns curve numbers, interception values, rooting depths and maximum recharge to each combination of hydrologic soil group and land use/land cover type. An additional data may be required by the program depending on the formulation of the evapotranspiration equation the user specifies for the calculation of water budget. This additional data types include: daily average wind speed; daily average relative humidity; daily maximum relative humidity; and daily percentage of possible sun shine.

The program output can be supplied in daily, monthly and yearly frequency. The output types are tabular and grid. For the grid output type, the user can choose between Surfer and ArcGIS formats.

The steps involved in determining a recharge (potential recharge) estimate that can be used in a GPWAR are as follows:

1. Prepare all program input files;
2. Run the program;
3. Load the results into ArcGIS or Surfer, to create ArcGIS raster or Surfer grid files;
4. Use ArcGIS 3D Analyst or Spatial Analyst to calculate the total recharge volume.

**Method outputs for use in the GPWARs**

Annual potential recharge is output from the SWB method to be used in the GPWARs. An estimate of usage can also be independently estimated for these areas, however given the extremely limited data available at the moment no other components are derived for the accounting.

**Summary and discussion**

Reporting both detailed and accurate annual groundwater budget information for groundwater across the entire scope of the NSW surface water catchments is a difficult task and is limited by observed data availability.

In NSW sufficient datasets to achieve a full groundwater balance are primarily limited to the major inland alluviums, where a relatively high level of irrigation demand occurs. These aquifers are associated with a groundwater model that can be used to assist producing the GPWARs.

As detailed in this report, NOW has developed and implemented two methods specifically for those areas where a groundwater model is not currently available. The first of these methods, the Water Table Fluctuation method, uses the available water levels data and is customised specifically for the water year to be accounted. This method is able to provide a full water balance for the GPWAR and has been currently implemented in the Peel Alluvium and Upper Lachlan Groundwater Management Areas.

The second method presented in this report, the Soil Water Budget model, provides an option for the areas that have few or no monitoring bores available. With no observations to assess results against the accuracy of this method is largely unknown. The performance was deemed acceptable for the intended purpose, however, when comparing its recharge estimate to that of the groundwater model for zone 3 of the upper Namoi Groundwater Management Area. While
currently an estimate of potential recharge is the only water balance parameter obtained from using the Soil Water Budget model, it is expected that such information will be a useful starting point for the annual accounting products that can be built on over time. With this information relative changes in potential recharge may be assessed by users each year water year. This method has generally been applied in the fractured rock areas such as the Lachlan Fold Belt.
Case Study
Introduction

In order to assess the applicability of the proposed methodologies of the Water Table Fluctuation and Soil Water Budget Methods, a case study was implemented for an area where a model calibrated to observed aquifer levels was available for comparison. While it is not possible to directly compare the method results with observed values it is assumed that the calibrated model will provide a reasonable estimate of the true balance and as such the effectiveness of each method can be gauged by its similarity to the model water budget figures.

Study area

The study area (groundwater management Zone 3) covers an area of approximately 555 km² and forms part of the Upper Namoi groundwater management area. This area falls within the Mooki River basin, which is a tributary of the Namoi River Basin. The Mooki River passes through the study area from Breeza to Gunnedah. This river is an ephemeral river that has no flow in some months of the year.

The mean elevation of the study area is about 277 m AHD. The area is bordered by Zone 4 to the north and Zone 8 to the south, while no-flow boundaries flanks the area to the east and west. The rainfall in the area is seasonal and the mean annual rainfall for this area is approximately 300 mm/yr.

According to the Land Use of Australia, Version 4, 2005-06, the Zone 3 land use is predominantly agricultural and comprises approximately 53.7% cropping; 42% grazing; 4.0% unallocated agricultural land; and 1.0% forest. The land use of the study area is shown in Figure 5.

Figure 5: Study Area - Zone 3 of the Upper Namoi Groundwater Management Area
Geology and Hydrogeology

The surficial geology of the study area comprises late Tertiary to Quaternary unconsolidated sediments of the Namoi River basin, overlying pre-Tertiary bedrock. According to Gates & Ross (1980), the alluvium is generally divided into two stratigraphic units: the basal Gunnedah Formation; and the overlying Narrabri Formation. The alluvium has an average thickness of 70m and maximum thickness of about 140m.

The Narrabri Formation forms the ground surface across the study area. It consists of extensive overbank clays with lesser channel sands and gravels, which were deposited by leved meandering streams. This formation is generally a lower yielding aquifer (McNeilage 2006).

The underlying Gunnedah Formation fills the main palaeovalley floor, including the deeper palaeochannel features. It consists of moderately well sorted sands and gravels with inter-bedded clays, which are likely to have been deposited by braided streams. These sand and gravel deposits are up to 140m deep and form high-yielding lower-salinity aquifer. The most productive aquifers generally lie within deep palaeochannel that contain coarse sediments deposited by high energy streams (McNeilage 2006).

Pre-Tertiary bedrock consisting of fractured sedimentary and volcanic rocks underlies the Gunnedah Formation. Although there may be a leakage between the bedrock and the overlying Gunnedah formation, however, it is very hard to know the location and the quantity of this leakage. Therefore, the bedrock is considered impermeable. This assumption may be justified in that the contrast in hydraulic conductivity between the alluvium and the bedrock within this area is likely to be generally greater than two orders of magnitude.

Figure 6: Study Area Top Soil Type

Figure 7: Study Area Land Use
Test comparison period
Both methodologies were compared against the model figures for the period of 01/07/2006–30/06/2007

Applying the water table fluctuation method
Conceptual model
A schematic conceptual model of the study area is shown in Figure 8. The conceptual model consists of an upper unconfined aquifer (Narrabri formation) underlain by a lower confined leaky aquifer (Gunnedah formation). These layers are mutually independent and each layer has its own water budget equation, however, the aquifers exchange water through a leakage term ($Q_{\text{leak}}$).

The water budget analysis for layers 1 and 2 is discussed in following sections.
Figure 8: Schematic diagram showing layer 1 and layer 2 groundwater budget components

where: \( R_{\text{rain}} \) is direct recharge from rainfall; \( RF \) is irrigation return flow; \( Q_{\text{on}} \) and \( Q_{\text{off}} \) are lateral groundwater flow onto and off the groundwater system; \( Q_{\text{river}} \) is river seepage recharge; \( ET \) is evapotranspiration; \( PG \) is extraction of groundwater by pumping; \( Q_{\text{bf}} \) is baseflow (groundwater discharge to streams or springs); \( Q_{\text{leak}} \) is inter-layer leakage term; \( \Delta S_1 \) and \( \Delta S_2 \) are change in groundwater storage for Layer 1 and Layer 2, respectively.

Layer-2 groundwater budget

Layer-2 is a separate groundwater system and has its own water budget. Figure 9 is a conceptual model of layer 2 showing the groundwater budget flow components. Assuming that there is no water exchange between the lower aquifer and the bedrock, the Layer 2 water budget can be written as:

\[
Q_{\text{on}2} + Q_{\text{leak}} = PG_2 + Q_{\text{off}2} + \Delta S_2 \tag{Equation 17}
\]

where: \( Q_{\text{on}2} \) and \( Q_{\text{off}2} \) are lateral groundwater flow onto and off the Layer 2; \( PG_2 \) is groundwater withdrawal from layer 2; \( Q_{\text{leak}} \) is the net leakage between the two aquifers; and \( \Delta S_2 \) is change in storage in Layer 2. The water budget flow components are expressed as rates (e.g. GL/year)
Change in storage ($\Delta S_2$)

$$\Delta S_2 = A_2 \times S \times \Delta h \quad (Equation \ 18)$$

where: $A_2$ is surface area of the Layer 2; $S$ is storage coefficient of the Layer 2; $\Delta h_{annual2}$ is the average annual groundwater level change in layer 2 (i.e. water levels at July 07 – water levels at July 06).

Storage change was calculated as follows:

First, a groundwater contour maps were created for the beginning (1st July 2007) and the end (30th June 2006) of the water year. The water levels that were used to create the contour maps were collected from 56 monitoring bores that are screened in Layer-2 (Figure 10).
Figures 11 and 12 show the contour maps for the beginning and the end of the water year, respectively.

Then, the contour map for the beginning of the water year (1st July 2007) was subtracted from the end of the water year contour map (30th June 2006) to create the annual water level change map of the area (Figure 13).
Next, using ArcGIS Spatial analyst, the annual water level change map was multiplied with the storage coefficient map (Figure 14) that was derived from a MODFLOW model for the area. The product map of the annual water level change and storage coefficient maps is shown in Figure 15.

Finally, the product map was used in ArcGIS 3D Analyst to calculate the net volume of the raster map, which is the annual change in storage for the lower aquifer. The lower aquifer change in storage for 2006 – 2007 was calculated to be 1.3GL.

Groundwater Pumping (PG2)

The annual groundwater pumping from layer 2 was extracted from the NOW database and was estimated to be 24.15GL. This figure is based on metered data and is equivalent to what was used in the MODFLOW groundwater model.

Lateral Inflow/ Outflow

The lateral inflow/ outflow can be mathematically written as:

$$ Q = A \times K \times i $$  \hspace{1cm} (Equation 19)

where: $Q$ is lateral inflow or outflow; $K$ is hydraulic conductivity; $A$ is saturated cross sectional area; and $i$ is hydraulic gradient.

The lateral flow calculations were done in ArcGIS Spatial analyst, therefore, raster maps were prepared for the saturated thickness, hydraulic conductivity and the hydraulic gradient of the aquifer. The raster maps for the hydraulic conductivity and saturated thickness of the lower aquifer were extracted from an existing MODFLOW model for the area and are shown in figures 16 and 17, respectively.

The average monthly hydraulic gradient and groundwater flow direction was inferred from the Slope and Aspect maps created from average monthly water level contour maps for the area. The analysis was done in ArcGIS environment, therefore, the lateral flow calculations was carried out cell by cell and the total monthly follow that passes through a cell can be calculated as follows:
\[ Q_{\text{cell}} = B_{\text{cell}} \times i_{\text{cell}} \times K_{\text{cell}} \times \text{cell - size} \times n \]  

(Equation 20)

Where: \( B_{\text{cell}}, i_{\text{cell}}, K_{\text{cell}} \) are the average saturated monthly thickness, slope and hydraulic conductivity maps, respectively; \( n \) is number of days in the month; and \( \text{cell-size} \) is the cell size of the raster map.

Using the ArcGIS Spatial Analyst the saturated thickness, hydraulic conductivity and slope maps were combined into one raster map. Next, cell size and number of days in the month was multiplied to the resultant raster. Finally, the grid cells along the seepage boundaries were extracted and the total lateral flow was calculated by summing up the lateral flows of the individual boundary cells that has the same flow directions. The groundwater flow direction for July 2006 inferred from aspect map of the same month and is shown in Figure 18.

The above mentioned process was carried out for each month in the water year and the calculated total monthly inflow and outflow volumes are shown in Table 1.
Table 1: Layer 2 Inflow and Outflow of Layer 2

<table>
<thead>
<tr>
<th>Months</th>
<th>Total Monthly Inflow (ML)</th>
<th>Total Monthly Outflow (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July – 06</td>
<td>224.76</td>
<td>9.01</td>
</tr>
<tr>
<td>August – 06</td>
<td>250.56</td>
<td>8.52</td>
</tr>
<tr>
<td>September – 06</td>
<td>243.77</td>
<td>8.62</td>
</tr>
<tr>
<td>October – 06</td>
<td>256.63</td>
<td>9.60</td>
</tr>
<tr>
<td>November – 06</td>
<td>263.85</td>
<td>8.74</td>
</tr>
<tr>
<td>December – 06</td>
<td>289.97</td>
<td>8.48</td>
</tr>
<tr>
<td>January – 07</td>
<td>321.26</td>
<td>8.62</td>
</tr>
<tr>
<td>February – 07</td>
<td>302.30</td>
<td>7.16</td>
</tr>
<tr>
<td>March – 07</td>
<td>323.63</td>
<td>6.94</td>
</tr>
<tr>
<td>April – 07</td>
<td>298.52</td>
<td>5.71</td>
</tr>
<tr>
<td>May – 07</td>
<td>283.85</td>
<td>6.42</td>
</tr>
<tr>
<td>June – 07</td>
<td>253.84</td>
<td>5.94</td>
</tr>
</tbody>
</table>

Based on the figures in Table 1, the total lateral inflow and lateral outflow were calculated to be **3.31GL** and **0.1GL**, respectively.

**Inter-layer leakage \( Q_{\text{leak}} \)**

Inter-layer leakage was calculated by rearranging equation 17 and solving it for the leakage term. Equation 17 can be rewritten as:

\[
Q_{\text{leak}} = PG + \Delta S + Q_{\text{off}} - Q_{\text{on}}
\]

\( (\text{Equation 20}_1) \)

Using the pumping, storage change and lateral flow volumes calculated in the previous sections, the inter-layer leakage was calculated to be **22.24GL**.

**Layer-2 results summary**

The calculated Layer-2 groundwater budget components are shown on Figure 19.
Layer-1 groundwater budget

In addition to the budget components of Layer 2, Layer 1 also receives a natural recharge and is subjected to evapotranspiration. Moreover, Layer 1 interacts with the rivers and other surface water bodies and may lose or gain water from them.

The layer 1 groundwater budget flow components are shown on Figure 20 and can be written as:

\[ R_{\text{rain}} + RF + Q_{\text{off1}} + Q_{\text{river}} = ET + PG_1 + Q_{\text{off1}} + Q_{bf} + Q_{\text{leak}} + \Delta S_1 \]  

\[ \text{(Equation 21)} \]
where: $R_{rain}$ is direct recharge from rainfall; $RF$ is irrigation return flow; $Q_{on1}$ and $Q_{off1}$ are lateral groundwater flow onto and off the layer 1; $Q_{river}$ is river seepage recharge; $ET$ is evapotranspiration; $PG_1$ is extraction of groundwater by pumping; $Q_{bf}$ is baseflow (groundwater discharge to streams or springs); $Q_{leak}$ is inter-layer leakage and $\Delta S_1$ is change in groundwater storage in layer 1.

Groundwater Pumping ($PG_1$)

According to the information held by the NSW Office of Water database, a total of 3.65GL was pumped from layer 1 in 2006/2007 water year. The monthly groundwater pumping pattern was adopted from the groundwater modelling report (McNeilage, 2006). The pumping pattern was used to distribute the total pumped water over the entire hydrological year as shown in Table 2.

<table>
<thead>
<tr>
<th>Months</th>
<th>Pumping Pattern</th>
<th>Monthly Pumping (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July - 06</td>
<td>0.015</td>
<td>54.73</td>
</tr>
<tr>
<td>August - 06</td>
<td>0.025</td>
<td>91.22</td>
</tr>
<tr>
<td>September - 06</td>
<td>0.085</td>
<td>310.15</td>
</tr>
<tr>
<td>October - 06</td>
<td>0.100</td>
<td>364.88</td>
</tr>
<tr>
<td>November - 06</td>
<td>0.055</td>
<td>200.69</td>
</tr>
<tr>
<td>December - 06</td>
<td>0.100</td>
<td>364.88</td>
</tr>
<tr>
<td>January - 07</td>
<td>0.250</td>
<td>912.21</td>
</tr>
<tr>
<td>February - 07</td>
<td>0.230</td>
<td>839.23</td>
</tr>
<tr>
<td>March - 07</td>
<td>0.090</td>
<td>328.40</td>
</tr>
<tr>
<td>April - 07</td>
<td>0.025</td>
<td>91.22</td>
</tr>
<tr>
<td>May - 07</td>
<td>0.015</td>
<td>54.73</td>
</tr>
<tr>
<td>June - 07</td>
<td>0.010</td>
<td>36.49</td>
</tr>
</tbody>
</table>

Irrigation return flow (RF)

Some studies that deal with irrigation return flow (Dewandel et al., 2008; Arnold, LR., 2011) assume that it is a fraction of total water pumped from the aquifer that was used for irrigation. This can be written as: $RF = CPG$ where $C$ is the return coefficient ($0<C<1$). The $C$ values reported in the literature ranges from 50% for flood irrigated paddy fields to 0% for drip irrigation. The $C$ values reported in the literature for the crops other than rice are usually below 30%. For the study area, the RF was assumed to be 20% of total irrigated water ($PG_1 + PG_2 +$ surface diversion). The total irrigated water is estimated as 28.07GL, which is made up of:

3.65 GL pumped from the upper aquifer (Layer 1); and

24.42 GL pumped from the lower aquifer (Layer2).

Based on the above discussion, the total RF was estimated to be 5.61GL. The monthly irrigation return flow was assumed to be consistent with irrigation pattern and is shown in the table below:
Table 3: Monthly Irrigation Return Flow

<table>
<thead>
<tr>
<th>Months</th>
<th>Pumping Pattern</th>
<th>Monthly Irrigation Return Flow (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July - 06</td>
<td>0.015</td>
<td>84.20</td>
</tr>
<tr>
<td>August - 06</td>
<td>0.025</td>
<td>140.34</td>
</tr>
<tr>
<td>September – 06</td>
<td>0.085</td>
<td>477.16</td>
</tr>
<tr>
<td>October – 06</td>
<td>0.100</td>
<td>561.36</td>
</tr>
<tr>
<td>November - 06</td>
<td>0.055</td>
<td>308.75</td>
</tr>
<tr>
<td>December - 06</td>
<td>0.100</td>
<td>561.36</td>
</tr>
<tr>
<td>January - 07</td>
<td>0.250</td>
<td>1403.40</td>
</tr>
<tr>
<td>February - 07</td>
<td>0.230</td>
<td>1291.13</td>
</tr>
<tr>
<td>March - 07</td>
<td>0.090</td>
<td>505.22</td>
</tr>
<tr>
<td>April - 07</td>
<td>0.025</td>
<td>140.34</td>
</tr>
<tr>
<td>May - 07</td>
<td>0.015</td>
<td>84.20</td>
</tr>
<tr>
<td>June - 07</td>
<td>0.010</td>
<td>56.14</td>
</tr>
</tbody>
</table>

Figure 21: Layer 1 Aquifer Thickness

Figure 22: Layer 1 GW Elevation (1st July 2006)

Lateral inflow/outflow ($Q_{on1}$/ $Q_{off1}$)

The layer 1 lateral inflow and outflow were calculated using the process that was explained earlier (Equation 19). Since layer 1 is partially saturated, the depth to water was subtracted from the total thickness of the aquifer to obtain the saturated thickness that can be used in calculating the saturated area that is normal to the flow direction. Using 56 monitoring bores in the study area, the depth to water, groundwater elevation and saturated thickness maps were prepared for each month of water year. Saturated thickness maps were created by subtracting the depth to water maps from the aquifer (Layer 1) thickness map (Figure 21). Groundwater elevation, depth
to water and saturated thickness contour maps for 1st July, 2006 are shown in figures 20, 21 and 22, respectively. Hydraulic conductivity distribution in Layer 1 is shown in Figure 24.

Figure 23: Layer 1 Depth to water (1st July 2006)  Figure 24: Layer 1 Saturated Thickness (1/07/2006)

Monthly groundwater elevation rasters were used to create the monthly slope and aspect maps. The lateral flow (Q) that flow through a cell was calculated according the flowing equation:

\[ Q_{\text{cell}} = B_{\text{cell}} \times i_{\text{cell}} \times K_{\text{cell}} \times n \]  

(Equation 22)

Where: \( Q_{\text{cell}} \) is total monthly lateral flow through a cell; \( B_{\text{cell}} \), \( i_{\text{cell}} \), \( K_{\text{cell}} \) and \( n \) are cell saturated thickness, cell hydraulic gradient, cell hydraulic conductivity and number of days in the month.

First, the saturated thickness, slope and hydraulic conductivity maps were combined using ArcGIS spatial analyst. Next, the cell size and number of days in the month was multiplied to the combined map to obtain a raster map that shows the total monthly flow through each cell. Finally, the cells along the seepage boundaries were extracted from the total flow volume raster map and the cells with the same flow direction were added up to obtain the total lateral inflow and outflow. The groundwater flow direction was determined from the aspect map and is shown in Figure 26.
Table 4: Layer 1 Lateral Inflow/Outflow

<table>
<thead>
<tr>
<th>Month</th>
<th>Monthly Inflow (ML)</th>
<th>Monthly Outflow (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July - 06</td>
<td>50.69</td>
<td>0.49</td>
</tr>
<tr>
<td>August - 06</td>
<td>44.07</td>
<td>0.62</td>
</tr>
<tr>
<td>September – 06</td>
<td>44.47</td>
<td>0.60</td>
</tr>
<tr>
<td>October – 06</td>
<td>47.26</td>
<td>0.63</td>
</tr>
<tr>
<td>November - 06</td>
<td>46.30</td>
<td>0.54</td>
</tr>
<tr>
<td>December - 06</td>
<td>48.41</td>
<td>0.62</td>
</tr>
<tr>
<td>January - 07</td>
<td>50.70</td>
<td>0.49</td>
</tr>
<tr>
<td>February - 07</td>
<td>46.68</td>
<td>0.42</td>
</tr>
<tr>
<td>March - 07</td>
<td>50.39</td>
<td>0.45</td>
</tr>
<tr>
<td>April - 07</td>
<td>46.91</td>
<td>0.38</td>
</tr>
<tr>
<td>May - 07</td>
<td>52.34</td>
<td>0.49</td>
</tr>
<tr>
<td>June - 07</td>
<td>42.09</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Based on the above table the total Layer-1 inflow and outflow were calculated to be 0.576GL and 0.006GL, respectively.

Evapotranspiration (\(ET\))

Given that the groundwater table in the study area is deep, it is assumed that transpiration is negligible and evaporation is the main process of the evapotranspiration. The evaporation from the groundwater table during water year was calculated from Coudrain-Ribstein et al. (1998) evaporation formula for unconfined aquifers:

\[
E = \frac{71.9}{Z^{1.49}}
\]

\( (Equation \ 23) \)
where: E is evaporation from the water table (mm/year); and Z is the depth to the water table (m).

For each month in the water year, the monthly groundwater evaporation was calculated using the above equation in conjunction with the average monthly depth to water contour map for that month to produce the average monthly evaporation contour map. Then, the average monthly evaporation map was multiplied by the number of days in the month to get the total monthly evaporation map for that month. Finally, the total monthly evaporation map was used in ArcGIS 3D Analyst to calculate the evaporation volume for the month. The calculated evaporation volume for each month of the water year is listed in Table 5.

Table 5: Layer 1 Monthly Evapotranspiration

<table>
<thead>
<tr>
<th>Month</th>
<th>Monthly Evapotranspiration (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July - 06</td>
<td>55.28</td>
</tr>
<tr>
<td>August - 06</td>
<td>53.62</td>
</tr>
<tr>
<td>September – 06</td>
<td>52.33</td>
</tr>
<tr>
<td>October – 06</td>
<td>51.05</td>
</tr>
<tr>
<td>November - 06</td>
<td>49.62</td>
</tr>
<tr>
<td>December - 06</td>
<td>48.32</td>
</tr>
<tr>
<td>January - 07</td>
<td>47.03</td>
</tr>
<tr>
<td>February - 07</td>
<td>47.15</td>
</tr>
<tr>
<td>March - 07</td>
<td>48.59</td>
</tr>
<tr>
<td>April - 07</td>
<td>50.30</td>
</tr>
<tr>
<td>May - 07</td>
<td>51.54</td>
</tr>
<tr>
<td>June - 07</td>
<td>52.68</td>
</tr>
</tbody>
</table>

The total evapotranspiration for 2006/07 water year was estimated to be 0.607GL.

Inter-layer leakage

During the Layer-2 water budget analysis, the total pumping induced leakage from Layer-1 to Layer-2 was calculated to be 22.24GL. It was assumed that the leakage pattern is consistent with pumping pattern; therefore, the leakage was distributed over the 12 months of the water year as shown in Table 6.

Table 6: Monthly Leakage Volume

<table>
<thead>
<tr>
<th>Month</th>
<th>Leakage (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July - 06</td>
<td>337.3286</td>
</tr>
<tr>
<td>August - 06</td>
<td>562.2143</td>
</tr>
<tr>
<td>September – 06</td>
<td>1911.529</td>
</tr>
<tr>
<td>October – 06</td>
<td>2248.857</td>
</tr>
<tr>
<td>November - 06</td>
<td>1236.871</td>
</tr>
<tr>
<td>December - 06</td>
<td>2248.857</td>
</tr>
<tr>
<td>January - 07</td>
<td>5622.143</td>
</tr>
<tr>
<td>February - 07</td>
<td>5172.371</td>
</tr>
</tbody>
</table>
Leakage (ML)

<table>
<thead>
<tr>
<th>Month</th>
<th>Leakage (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March - 07</td>
<td>2023.971</td>
</tr>
<tr>
<td>April - 07</td>
<td>562.2143</td>
</tr>
<tr>
<td>May - 07</td>
<td>337.3286</td>
</tr>
<tr>
<td>June - 07</td>
<td>224.8857</td>
</tr>
</tbody>
</table>

Baseflow ($Q_{bf}$) and River Loss ($Q_{river}$)

The river loss and baseflow were calculated using the Channel-water Budget method (Lerner et al., 1990) shown below:

$$Q_{river} = Q_{down} - Q_{up} - \sum Q_{in} + \sum Q_{out} + E_a - \frac{\Delta S}{\Delta t}$$  \hspace{1cm} (Equation 24)

where: $Q$ is gauged flow rate, $Q_{up}$ and $Q_{down}$ are flows at the upstream and downstream ends of the reaches, $Q_{in}$ is tributary inflows and $Q_{out}$ is extractions and effluents from the river, $E_a$ is the evaporation from surface water or stream bed, and $\Delta S$ is change in channel and unsaturated-zone storage over change in time ($\Delta t$).

The $Q_{up}$ and $Q_{down}$ were measured at the gauging stations 419027 (Breeza) and 419084 (Ruvinge), which are located upstream and downstream of the study area, respectively. The net evaporation from the surface of the river was estimated from the following equation:

$$E_{net} = \Sigma (K_c E_i - p_i) \left( \frac{w_{1i} + w_{2i}}{2} \right) L$$ \hspace{1cm} (Equation 25)

Where $E_{net}$ is net monthly evaporation volume, $K_c$ is crop factor, $E_i$ is the daily FAO evapotranspiration, $p_i$ is the daily precipitation, $w_{1i}$ and $w_{2i}$ are the daily river widths at the upgradient and downgradient river stations, and $L$ is the river length between the 2 gauging stations.

The daily river widths were inferred from the stage-width rating tables, which were extracted from Hydstra (time series data management system). The daily evapotranspiration and precipitation data from the weather the station 55008 was used in evaporation calculations. The climatic data for station 55008 was downloaded from the SILO website (http://www.longpaddock.qld.gov.au/silo/ppd/index.php). The crop factor ($K_c$) of 1.05 (crop factor for open water) was adopted from Table 12 of Allen et al. (1998). The length of river reach between the 2 gauging stations ($L$) was calculated from the line shapefile representing the reach using ArcGIS and is approximately 46km.

The flow gauging data from the 2 gauging stations indicate that no water is being added to the river between the 2 gauging stations, therefore, the monthly tributary inflow ($Q_{in}$) was assumed to be zero. Water diversion between the gauging stations ($Q_{out}$) was also assumed to be zero due to the lack of any recorded diversions. The monthly channel – water budget results are summarised in Table 7.

The last column of Table 7 is the result of applying Equation 24 to the Chanel-Water Budget components. Where results are negative indicate that water was lost between the gauging stations. Conversely, where the result is positive indicates that water was added to the river between the 2 gauging stations. As all other channel-water budget components were explicitly considered, the water loss between the gauging stations was considered to be $Q_{river}$. Also, the water gain between the gauging stations was taken as the baseflow ($Q_{bf}$). Following the above discussion, the total river loss and total baseflow estimated to be 6.7GL and 0.0003GL, respectively.
<table>
<thead>
<tr>
<th>Months</th>
<th>Inflow at 419027 (Q&lt;sub&gt;up&lt;/sub&gt;) (ML)</th>
<th>Outflow at 419084 (Q&lt;sub&gt;down&lt;/sub&gt;) (ML)</th>
<th>Surface Evaporation E&lt;sub&gt;a&lt;/sub&gt; (ML)</th>
<th>Surface Water diversion s (Q&lt;sub&gt;out&lt;/sub&gt;) (ML)</th>
<th>Estimated inflows (Q&lt;sub&gt;in&lt;/sub&gt;) (ML)</th>
<th>Estimated baseflow/River Loss (Q&lt;sub&gt;river&lt;/sub&gt;) (ML)</th>
<th>Estimated inflows (Q&lt;sub&gt;in&lt;/sub&gt;) (ML)</th>
<th>Estimated baseflow/River Loss (Q&lt;sub&gt;river&lt;/sub&gt;) (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul -06</td>
<td>79.86</td>
<td>0.00</td>
<td>-0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>-80.36</td>
<td>0.00</td>
<td>-80.36</td>
</tr>
<tr>
<td>Aug -06</td>
<td>33.18</td>
<td>0.00</td>
<td>1.38</td>
<td>0.00</td>
<td>0.00</td>
<td>-31.79</td>
<td>0.00</td>
<td>-31.79</td>
</tr>
<tr>
<td>Sep -06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Oct -06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Nov -06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Dec -06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Jan -07</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Feb -07</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Mar -07</td>
<td>481.72</td>
<td>100.60</td>
<td>14.26</td>
<td>0.00</td>
<td>0.00</td>
<td>-366.85</td>
<td>0.00</td>
<td>-366.85</td>
</tr>
<tr>
<td>Apr -07</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>May -07</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Jun -07</td>
<td>21925.37</td>
<td>15707.15</td>
<td>-20.87</td>
<td>0.00</td>
<td>0.00</td>
<td>-6238.88</td>
<td>0.00</td>
<td>-6238.88</td>
</tr>
</tbody>
</table>

**Dry/Wet Period Identification**

To determine the remaining water budget components, the average specific yield needs to be calculated. The method calculates the specific yield from the dry period of hydrological year, therefore, the dry and wet periods of water year need to be identified.

The water levels from 56 monitoring bores in study area were contoured at beginning of each month. Then the mean water level of the contour map was used as this month’s representative water level. Finally, a graph of mean water levels versus months was created as shown in Figure 27. A close examination of the mean water levels graph indicates that the water levels for this water year (2006 – 2007), fell the period between July 2006 and February 2007, and rose between February 2007 and June 2007. Therefore, the period from July 2006 to Feb 2007 was chosen to be the dry period, while the period between Feb 2007 and June 2007 was chosen to be wet period.
Specific yield ($S_y$)
The average specific yield for the study area was calculated from groundwater budget components’ contributions during the dry period. Each budget component in Equation 6 had its monthly values summed up for the period from 2006 to February 2007 to obtain the total dry period volume of that budget component. The dry period water level change map was prepared by subtracting July 2006 water levels from the February 2007 water levels. The total dry period volume of the groundwater budget components is summarised in Table 8.

Using Table 7 and Equation 6, the specific yield was calculated to be 0.012.

Rainfall Recharge
The rainfall recharge was calculated from the contributions of groundwater budget components during the wet period. Each budget component’s total wet period volumes are listed in Table 9. Using Table 8 and Equation 8, the rainfall recharge was estimated as 11.45GL.

Layer 1 change in storage for water year 2006–07
The 2006/07 change in storage is the difference between aquifer storage at the beginning and end of the water year. The Layer 1 annual change in storage was calculated from the following equation:
\[ \Delta S_1 = A \times S_y \times \Delta h_{\text{annual}} \quad (Equation \ 26) \]

where: \( A \) is the surface area of the aquifer; \( S_y \) is the specific yield of the aquifer; and \( \Delta h_{\text{annual}} \) is the difference between the water levels at beginning and end of the water year.

To obtain the annual water level change contour map, the water level contour map for the 1 July 2006 was subtracted from the 30 June 2007 water level contour map, using ArcGIS spatial analyst. Then, the average specific yield calculated earlier was multiplied to the annual water level change map. Finally, the resultant contour map was used in ArcGIS 3D Analyst to calculate the net volume that corresponds to the annual water level change. The Layer 1 change in storage for the 2006/07 water year was estimated to be 2.4GL.

**WTF comparison with MODFLOW**

The results produced by the WTF method compared to those produced by the MODFLOW model for the same period are summarised in 9.

<table>
<thead>
<tr>
<th>Budget Components</th>
<th>MODFLOW Results</th>
<th>WTF Method Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall Recharge</td>
<td>7.836</td>
<td>11.45</td>
</tr>
<tr>
<td>Irrigation recharge</td>
<td>5.654</td>
<td>5.61</td>
</tr>
<tr>
<td>River Leakage: inflow</td>
<td>1.227</td>
<td>6.72</td>
</tr>
<tr>
<td>River Leakage: outflow</td>
<td>0.055</td>
<td>0.00003</td>
</tr>
<tr>
<td>Lateral Flow: Layer 1: Inflow</td>
<td>1.830</td>
<td>0.57</td>
</tr>
<tr>
<td>Lateral Flow: Layer 1: Outflow</td>
<td>0.208</td>
<td>0.006</td>
</tr>
<tr>
<td>Lateral Flow: Layer 2: Inflow</td>
<td>3.939</td>
<td>3.31</td>
</tr>
<tr>
<td>Lateral Flow: Layer 2: Outflow</td>
<td>1.096</td>
<td>0.09</td>
</tr>
<tr>
<td>Inter Layer Leakage: Layer 1 to 2</td>
<td>21.047</td>
<td>22.49</td>
</tr>
<tr>
<td>Inter Layer Leakage: Layer 2 to 1</td>
<td>1.193</td>
<td>0.0</td>
</tr>
<tr>
<td>Evapotranspiration (Layer 1)</td>
<td>0.671</td>
<td>0.61</td>
</tr>
<tr>
<td>Pumping: Layer 1</td>
<td>3.65</td>
<td>3.65</td>
</tr>
<tr>
<td>Pumping: Layer 2</td>
<td>24.42</td>
<td>24.42</td>
</tr>
<tr>
<td>Change in Storage: Layer 1</td>
<td>-6.789</td>
<td>-2.4</td>
</tr>
<tr>
<td>Change in Storage: Layer 2</td>
<td>-2.175</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Layer- 1 results summary

Figure 28: Layer 1 Groundwater balance summary

Applying the soil water budget method

Application of the SWB code is demonstrated by applying it to zone 3 of the Upper Namoi groundwater management area. The model domain consists of 101,725 grid cell in an array of 313 cells wide and 325 cells tall; each cell in the model domain has dimensions of 100 by 100m. Modeled area includes all the areas that drain to the Ruvinge (419084) gauging station, which is located at the bottom of the study area.

The input climate datasets used for the test case span the years 1970 to 2013, inclusive. The SWB model input and options used for the recharge calculations are detailed below.

Climatological Input

Climatological inputs were derived from nation-wide climatological data sets. Daily precipitation, daily minimum temperature and daily maximum temperature were downloaded from the Australian Bureau of meteorology (BoM) website (http://www.bom.gov.au/climate/maps/) for the period of 1970 – 2013, inclusive. The downloaded climatological grid files were 5km by 5km grid cells in geographic coordinate system (Geocentric Datum of Australia 1994 (GCS_GDA_1994)). A script developed for ArcGIS 10.0 (ESRI, 2010) was used to extract (clip) the model specific raster data from the nation-wide climatological data sets. The script also performed a projection of clipped data to GDA_1994_MGA_Zone_55 coordinate system, resampling the data to a 100m by 100m grid and converting the resultant rasters to a series of ArcGIS ASCII grid text files, which can be used with SWB code.

Land Use/Land Cover Input

SWB code uses the land-use lookup table to assign the parameters such as runoff curve numbers, maximum daily recharge, rooting depth and interception values to each cell in the model domain. The program also uses the land-use grid along with the hydrologic soil group grid and land-use lookup table to calculate the runoff and soil storage capacity for each cell. The land-use grid was extracted from the Land Use of Australia, Version3, dataset that was downloaded from the Australian Government Department of Agriculture website.
The land use types that are similar were grouped to one major land-use type. Then, a unique number was assigned to each land-use type. This unique number will be used by the program to identify the land-use type to each cell in the model.

Table 10: Land-use Types

<table>
<thead>
<tr>
<th>LU code</th>
<th>Land-use Types</th>
<th>Australian Land Use and Management Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>Residential</td>
<td>5.4.1 &amp; 5.4.2</td>
</tr>
<tr>
<td>200</td>
<td>Other Non cereal crops</td>
<td>3.3.0 &amp; 4.3.0</td>
</tr>
<tr>
<td>210</td>
<td>Cereal</td>
<td>3.3.1 &amp; 4.3.1</td>
</tr>
<tr>
<td>240</td>
<td>Legumes</td>
<td>3.3.8</td>
</tr>
<tr>
<td>250</td>
<td>Oil seeds</td>
<td>3.3.4 &amp; 4.3.4</td>
</tr>
<tr>
<td>260</td>
<td>Cotton</td>
<td>3.3.6 &amp; 4.3.6</td>
</tr>
<tr>
<td>280</td>
<td>Nuts</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>Pasture Grass (Residual/ Native Pasture, Sown Pastures)</td>
<td>2.1.0, 4.2.0, 3.2.0, 4.2.0</td>
</tr>
<tr>
<td>330</td>
<td>Non-cereal forage crops</td>
<td>3.3.3</td>
</tr>
<tr>
<td>400</td>
<td>Forest (Nature Conservation, Agro forestry, production forestry, Other minimal Use)</td>
<td>1.1.1, 1.1.3,1.1.7, 3.1.0, 2.2.0 &amp; 1.3.0, 1.3.3</td>
</tr>
<tr>
<td>500</td>
<td>Water (mash/wetland, lake, reservoir/dam)</td>
<td>6.5.0, 6.1.0 &amp; 6.2.0</td>
</tr>
</tbody>
</table>

The program also uses a land-use lookup table to assign parameters such as curve number, rooting depth, interception and maximum daily infiltration, to each cell in the model. Land-use lookup table for this model is shown in Table 11.

Table 11: Land-use Lookup Table

<table>
<thead>
<tr>
<th>LU code</th>
<th>Assumed Imperviousness</th>
<th>Curve Number</th>
<th>Maximum Recharge (mm)</th>
<th>Interception (mm)</th>
<th>Rooting Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A B C D</td>
<td>A B C D</td>
<td>A B C D</td>
<td>(growing season)</td>
<td>Non-growing season</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>0.85</td>
<td>89 92 94 95</td>
<td>360 183.0 91.4 3.0</td>
<td>0 0</td>
<td>1015.0 1015.0 1015.0 676.7</td>
</tr>
<tr>
<td>200</td>
<td>**</td>
<td>67 77 83 87</td>
<td>360 182.0 91.4 3.0</td>
<td>0 0</td>
<td>1015.0 1100.3 1036.3 643.1</td>
</tr>
<tr>
<td>210</td>
<td>**</td>
<td>65 76 84 88</td>
<td>360 182.8 91.4 3.0</td>
<td>0 0</td>
<td>1000.0 1000.0 800.0 500.0</td>
</tr>
<tr>
<td>240</td>
<td>**</td>
<td>66 77 85 89</td>
<td>360 182.8 91.4 3.0</td>
<td>0 0</td>
<td>930.0 816.0 703.0 590.0</td>
</tr>
<tr>
<td>250</td>
<td>**</td>
<td>72 81 88 91</td>
<td>360 182.8 91.4 3.0</td>
<td>0 0</td>
<td>1700.0 1450.0 1200.0 960.0</td>
</tr>
</tbody>
</table>
NSW General Purpose Water Accounting Reports: Groundwater Methodologies

<table>
<thead>
<tr>
<th>LU code</th>
<th>Assumed Imperviousness</th>
<th>Curve Number</th>
<th>Maximum Recharge (mm)</th>
<th>Interception (mm)</th>
<th>Rooting Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A B C D</td>
<td>A B C D</td>
<td>A B C D</td>
<td>Interception</td>
<td>Rooting Depth</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(growing season)</td>
<td>(Non-growing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>season)</td>
</tr>
<tr>
<td>260</td>
<td>** 72 81 88 91</td>
<td>360</td>
<td>182.8 91.4</td>
<td>3.0</td>
<td>1700.0 1450.0 1230.0 1000.0</td>
</tr>
<tr>
<td>280</td>
<td>** 57 73 82 86</td>
<td>360</td>
<td>182.8 91.4</td>
<td>3.0</td>
<td>2000.0 1667.0 1333.0 1000.0</td>
</tr>
<tr>
<td>300</td>
<td>** 68 86 87 89</td>
<td>360</td>
<td>182.8 91.4</td>
<td>3.0</td>
<td>1450.0 1167.0 833.0 500.0</td>
</tr>
<tr>
<td>330</td>
<td>** 68 86 89 89</td>
<td>360</td>
<td>182.8 91.4</td>
<td>3.0</td>
<td>2000.0 1333.0 1000.0 1000.0</td>
</tr>
<tr>
<td>400</td>
<td>** 57 76 87 91</td>
<td>360</td>
<td>182.8 91.4</td>
<td>3.0 0.5</td>
<td>2500.0 2000.0 1400.0 1170.0</td>
</tr>
<tr>
<td>500</td>
<td>** 100 100 100 100</td>
<td>360</td>
<td>182.8 91.4</td>
<td>3.0 0.5</td>
<td>0.0 0.0 0.0 0.0</td>
</tr>
</tbody>
</table>

Figure 29: Land-use Grid

Soil Hydrologic Group
The model uses hydrologic soil group (A-B-C-D) as input and then applies runoff coefficients from the land cover lookup table for each soil type and land cover type. The soil data were resampled to 100 meter x 100 meter grid cells for the entire area.
Hydrologic soil groups and soil type was extracted from the Draft Soil Landscape Mapping for NSW (Shape file with Hydrologic Soil Groups, EPAWC and Soil Texture) provided by the Natural Resources Data Programs (soils) unit of the former NSW Department of Environment, Climate Change and Water. Each cell was then assigned to an integer value based on the value of hydrologic soil group using the following relationship: A=1, B=2, C=3 and D=4. The resultant hydrologic soil group grid is shown in Figure 31.

**Surface Flow Direction**

The SWB model requires a digital elevation model (DEM) to route surface water flows. When a cell produces runoff or outflow, it becomes inflow to the downslope cell based on the DEM. If capacity for infiltration exists in the downslope cell it will occur and excess is again routed downslope, and so on.

The flow direction grid was created from 1 second DEM that was clipped from Australia – wide 1 second SRTM Level 2 Derived Digital Elevation Model v1.0. The grid was resampled to 100m cell size and the ArcGIS Spatial Analyst FLOWDIRECTION function was used to generate the D-8 flow direction grid (Figure 32).
Available Soil Water Capacity

The SWB model uses soil information, together with land cover information, to calculate a maximum soil water holding capacity for each grid cell. The available water capacity grid was created by assigning the available water capacity values to the four soil types in the hydrologic soil group grid. The available water capacity values were taken from Table 12 below, which is based on Table 7 of Westenbroek et al (2010).

Table 12: Estimated available water capacities for various soil-texture groups

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Available Water Capacity (mm/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>1.00</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>1.17</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>1.33</td>
</tr>
<tr>
<td>Fine Sandy Loam</td>
<td>1.50</td>
</tr>
<tr>
<td>Very Fine Sandy Loam</td>
<td>1.67</td>
</tr>
<tr>
<td>Loam</td>
<td>1.83</td>
</tr>
<tr>
<td>Silt Loam</td>
<td>2.00</td>
</tr>
<tr>
<td>Silt</td>
<td>2.13</td>
</tr>
<tr>
<td>Sandy Clay Loam</td>
<td>2.25</td>
</tr>
<tr>
<td>Silty Clay Loam</td>
<td>2.38</td>
</tr>
<tr>
<td>Soil Texture</td>
<td>Available Water Capacity (mm/cm)</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>2.50</td>
</tr>
<tr>
<td>sandy Clay</td>
<td>2.67</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>2.83</td>
</tr>
<tr>
<td>Clay</td>
<td>3.00</td>
</tr>
</tbody>
</table>

The available water capacity grid is shown in Figure 33.

Figure 32: Available Water Capacity Grid

**Soil Water Budget results**

The model was used calculate the spatial and temporal variations in infiltration for Zone 3 and the areas that drain to Zone 3. The model was run for the period January 1, 1970 – December 30, 2013. The recharge for the water year 2006 – 2007 is shown in Figure 33.
The Zone 3 recharge raster was extracted from the raster shown in figure 33 and is shown in Figure 34. Using ArcGIS 3D Analyst, the total Zone 3 recharge for 2006 - 2007 was estimated to be 12.5GL. The result produced by the SWB method was compared to that produced by the MODFLOW model for the same period and is shown in Table 7. The recharges calculated by MODFLOW model and SWB model are presented in Table 13.

**Table 13: Summary results of MODFLOW against SWB – all figures are in GL**

<table>
<thead>
<tr>
<th>Budget Components</th>
<th>MODFLOW Results</th>
<th>SWB Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall Recharge</td>
<td>7.836</td>
<td>12.70</td>
</tr>
</tbody>
</table>

**Conclusion and discussion**

Comparisons of the MODFLOW results with the results generated by the WTF and SWB methods are presented in Tables 5 and 7, respectively. The review of the results indicates the following:

The WTF and MODFLOW results are comparable and within the same order of magnitude for the most of the groundwater budget components. However, there are some disagreement between the MODFLOW model and SWB method calculated figures in recharge, river loss and aquifer storage change. This discrepancy is mainly due to the difference in the assumptions employed and hydraulic parameter that was used in the methods – the MODFLOW results indicate lower rainfall recharge and river loss and higher aquifer storage loss, while the WTF results indicate higher river loss rainfall recharge, and lower aquifer storage loss.
The SWB method generated potential recharge is approximately 60% higher than the MODFLOW calculated rainfall recharge. This difference is probably due to MODFLOW model underestimating recharge for this water year because the model was not calibrated to this particular year.

While the close alignment of the MODFLOW model results and those of the more empirical methods is encouraging, there is not enough information to accurately assess how close any of the produced results may be to reality. With little groundwater data available in many areas, the empirical methods discussed in this report represent a starting point for future development as more information becomes available. Use of the data from these methods in the annual GPWARs is appropriate however the product should clearly disclose the high amount of uncertainty associated with the estimates.

References


