# Determining whole-of-system water use efficiency (DAN 14)

Final Report

for the

## National Program for Sustainable Irrigation (Land and Water, Australia)

NATIONAL PROGRAM FOR
Sustainable Irrigation

Helen Fairweather

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Helen Fairweather, 30th September 2005.

The project was funded by the National Program for Sustainable Irrigation (NPSI).

**PRINCIPAL INVESTIGATOR**

There have been several Principal Investigators over the duration of this project. David Mitchell worked on the project from Nov 2000 until May 2002. Alan Emerson was appointed as the Principal Investigator in Oct 2002 and Reuben Mubiru took over from Alan in March 2004. Rueben completed his appointment in April 2005. Since that time Helen Fairweather has completed the project as Principal Investigator. There have been two Supervisors over the duration of the project; Nick Austin supervised David Mitchell; Helen Fairweather supervised Alan and Reuben. Further information on this project is available from Helen Fairweather at NSW DPI, Dubbo (phone: 0268811211; email: helen.fairweather@dpi.nsw.gov.au)

**COLLOBARATORS**

Many people have contributed to this project through their role on steering committees, provision of data and discussion of the concepts. Those who provided assistance are too numerous to name, but recognition of their assistance is provided throughout the appendices of this report and previous milestone reports. The then Department of Land and Water, NSW (DLWC) were contracted as collaborators and provided much of the data analysed for this project.

Michael Pearson from SCOLARI SOFTWARE collaborated on the development of the software tool produced through this project.

Alan Beswick from Qld NRM provided a considerable volume of data for the Macquarie Valley analyses.



The National Program for Sustainable Irrigation focuses research on the development and adoption of sustainable irrigation practices in Australian agriculture.
The Program has 14 funding partners: Land & Water Australia (managing partner); Sunwater, Queensland; Horticulture Australia Limited; Goulburn-Murray Water, Victoria; Cotton Research and Development Corporation; Harvey Water, Western Australia; Lower Murray Water Authority, Victoria; Wimmera Mallee Water, Victoria; Ord Irrigation Cooperative, Western Australia; Australian Government Department of Agriculture, Fisheries and Forestry; Department of Natural Resources, Mines and Water, Queensland; Department of Primary Industries and Resources South Australia; Department of Environment Water and Catchment, Western Australia; and Department of Agriculture and Food, Western Australia.

# 1 INTRODUCTION

This report describes project achievements against the objectives of the 'Determining whole-of-system water use efficiency' project:

1. improved understanding of whole-of-system water balances within the Macquarie and Murrumbidgee valleys;
2. greater definition of irrigation delivery and application systems, and their interaction at farm, scheme and catchment levels;
3. assessment and prioritisation of opportunities for increased water use efficiency ;
4. quantification of potential water savings through increased farm, sub catchment and valley wide efficiency in the Macquarie and Murrumbidgee river valleys of NSW; and
5. documentation of the factors influencing crop planting and watering behaviour and those that are required for successful whole-of-system water use efficiency assessment.

The water balance is the fundamental tool for assessing water use efficiency at any scale. The uncertainty associated with the measurement of each of the elements of the water balance varies within and across these scales. Spatial and temporal heterogeneity, measurement error, and difficulty in obtaining some of the measurements all contribute to this uncertainty, making the seemingly simple task of accounting for water flow in a system a complex exercise. In this project we adopted a methodology to assess the water balance by considering three spatial scales (farm, scheme and catchment) and two temporal scales (daily and annual).

The traditional water balance approach is to determine the variables that make up the inputs and outputs and then construct a simple mathematical equation (Equation 1) to represent this water balance. This approach requires that all the variables in the equation are dimensionally equivalent, can be identified as an input or an output and are able to be quantified with some certainty. However, this is rarely the case when examining the water balance of farms, irrigation regions and catchments.

$$P + SWin + CR = SWout + DD + ET + \Delta S \qquad \text{........ Equation 1}$$

*where*
P is precipitation;
SWin is surface water flowing in to the system;
CR is capillary rise;
SWout is surface water flowing out of the system;
DD is deep drainage;
ET is evapotranspiration; and,
$\Delta S$ is the change in storage.

The application of this simple water balance equation is complicated by the uncertainty surrounding the input data and in some cases the non-existence of the required data. The water balance provides guidance on data collection and collation and characterises a system. However, it is doesn't provide an expression of the uncertainty of the variables that make up that water balance. In this project, Bayesian Networks were chosen as the tool to characterise this uncertainty.

# 2 METHODOLOGY

The methodology used in this project to assess the water balance at the three scales (farm, scheme and catchment) is novel in two respects:

- the focus of the water balance is on the flux of water between the scales. For example, the diversions from the catchment to the schemes, the diversions from the scheme to the farms and the link back from the farm to the whole of catchment by incorporation of groundwater levels and end of system flows in the analysis; and
- the water balance is assessed by considering the probabilities of each of the elements of the water balance being in a certain state conditioned on the state of related elements. For example, the probability the groundwater level is rising, static or falling is conditional on the total volume of tributary inflows over a year.

The project initially intended to develop the 'whole-of-system' water balance using Bayesian Networks[1] as a means of providing the framework for assessment of the water balance. This approach was used initially and the networks were developed at three nested and linked spatial scales (i.e. catchment, scheme and farm) using the Netica® software (Norsys 1998) for the Macquarie and Murrumbidgee catchments. Nesting the scales identifies the conceptual linkages or volume of water that flows between the spatial scales. This approach can be used to assess unaccounted for water at the various scales and therefore provides a valid assessment of potential water savings.

However, there were considerable problems associated with the above approach as the smallest dataset governed the size of the full dataset used in the analysis. For example, there were only ~five years of annual data for irrigation diversions for each of the schemes for the Macquarie catchment and though there were over 100 years of data available for the other elements (such as tributary inflows and end of system flows) only the corresponding five years were used in the full analysis. Groundwater data, though available, were also not included in this original approach because groundwater data measurements are provided as a depth dimension and the other elements of the water balance are all volumetric and there were difficulties aligning these different dimensions using this methodology. Also the groundwater sampling regimes were irregular with different periods of data collection across all the bores.

Given these difficulties another methodology that incorporated the groundwater data was developed. The Bayesian Networks developed for this revised methodology were capable of dealing with irregular datasets and the parameters that are not dimensionally equivalent. However this revised methodology didn't include the dedicated links between the spatial scales. The revised methodology also didn't lend itself to portability; application to a new valley would require all the calculations to be undertaken manually.

An analysis of the difficulties associated with the first two methodologies developed for this project led to the final product that is presented in this report and Attachment 1.

A full description of the initial methodologies and the results obtained are provided in Attachment 2.

The final methodology that was developed has been captured in a software program and an accompanying database. The software has been developed using the object orientated programming environment in Visual .Net using the c#® language (Microsoft Development Environment 2003). The object orientated nature of this programming environment enabled the structure of the software to reflect the spatial and temporal structure of the problem. For example, catchments, schemes and farms are created as objects and the time series data that link them are represented as their own objects (eg. day).

The software program, the Whole-Of-System Water Balance (WOS WB) tool, has also used mass balance principles to guide its structure and the collation of data. A mass balance simply states that the sum of the inputs must equal the sum of the outputs plus any change of state. A water balance is a particular application of mass balance principles, which have been applied extensively in agricultural systems modelling. For example, many irrigation models that simulate the dynamics of soil moisture use a water balance methodology.

## *2.1 WATER BALANCE STRUCTURE*

A description of the elements that provides the structure of the water balance (Equation 1) is required as the first step. Once the water balance structure has been defined a data collation exercise is undertaken for each of the elements. There are both spatial and temporal attributes that describe the elements of the water balance. The spatial attributes used in the WOS WB are the latitude and longitude that defines the centre of the point of interest (e.g. climate data at a particular location) and if required an area dimension (eg. irrigation scheme areas). The variability (temporal attribute) of the water balance is described by the time series of data for each of the elements. The WOS WB is able to aggregate both the spatial and temporal attributes of the underlying data at, and between, each of the scales. The aggregations vary as a function of the time steps and lengths of the datasets.

[1] Bayesian Networks provide a method to represent relationships between variables even if relationships involve uncertainty, unpredictability or imprecision. Links between variables can be established deterministically or probabilistically by observation or expert opinion.

## *2.2 DATA COLLATION*

Numerous sources were used in assembling data for this project. A summary of the data required to populate the WOS WB tool is provided in Table 1. For a complete description of all the datasets and associated references see Attachments 1 and 2.

**Table 1. Data requirements of the WOS WB tool (Ca = Catchment; Sc = Scheme; F = Farm).**

| Scale | Variable | Attribute | Dimension | Comment |
|---|---|---|---|---|
| Ca | Total dam diversions | Annual | Volume (ML) | All annual data are aligned to the July to June water year. For the Macquarie Valley there were insufficient data for the total, and irrigation, diversions from the dam on an annual basis. There were also insufficient data for irrigation diversions form the individual schemes. Therefore these time series were removed from the water balance analyses. However, they were considered in WUE analyses across the various scales (see Attachment 1). |
| | Tributary inflows | | | |
| Ca/Sc | Irrigation diversions | | | |
| Ca/Sc/F | Evaporation | Daily to Annual | Depth (mm) | Daily climate data are used at the farm scale and aggregated from 5km grid points defined by the water balance boundaries for the other spatial scales. |
| | Evapotranspiration | | | |
| | Rainfall | | | |
| | Location | Lat/long | | Climate points are used to store the location of the climate data, scheme centres and representative farms. |
| Ca/ F | Groundwater depths | Irregular | Depth (m) | At the farm scale the groundwater sampling interval governs the temporal scales of the water balance. |

The full version of the WOS WB includes a daily time step model that predicts the partitioning of water into crop evapotranspiration, soil moisture change and excess (rainfall + drainage) based on the FAO56 methodology (Allan *et al.* 1998). Crop coefficients collated as part of the NSW volumetric licence conversion process (Austin *et al.* 2002) and SILO climate data (BoM 2005) are used to drive this model. The use of such a model requires a process of calibration and validation to increase the confidence in the outputs. As this project was essentially a desktop study there were insufficient resources to conduct such an extensive analysis. Because of these difficulties and due to the computation demands of this model it was not possible to include the daily time step model outputs in the current analysis.

Once the database is populated with the time series data described in Table 1, the elements of the water balances at the various scales are automatically aggregated in the database. For example, at the valley scale, each element is aggregated to an annual time step. The software then interrogates each of these aggregated elements in the water balance and determines the tercile boundaries for all except groundwater. This is a simple ranking procedure where the records that indicate the boundaries of the first and middle terciles and the boundaries of the middle and third terciles are extracted. These boundaries are then used by the software to translate the result to a qualitative measure for each time step (low, medium, high and unknown). For example, if a value falls in the lowest tercile it is assigned a value of 'low'. For groundwater the boundaries for rising, falling and static levels are coded into the software (+0.1 and -0.1 m) and a similar qualitative transformation is applied.

The qualitative measures are then used to construct the Bayesian Network and associated conditional probability tables (CPTs) (see Appendix B for a description of how the network is linked by the CPTs), which is a reflection of the users understanding of the flux of water through the system. These networks can be viewed using the Netica® software (Norsys 1998).

The WOS WB and accompanying database have been constructed in such a way that additional elements can be included in the analyses without the requirement for alteration of the user interface. For example, the ABS (2005) wheat yield data are included in analysis presented in Attachment 1. The dynamic nature of the database structure provides scope for additional variables and dynamic creation of Bayesian Networks to allow a full interrogation of the behaviour of the water balance at different scales.

A graphical representation of the complete data collection is also possible through the WOS WB user interface, which relies on the spatial attributes associated with each dataset.

# 3 PROJECT OUTPUTS

The most important output from this project is a tool to assess the water balance at a range of scales for a particular valley. The tool demonstrates that disparate data available through various agencies, local knowledge and modelling can be combined to provide insight into how irrigation can impact on the water balance at different scales (Objective 1). Probabilities are used to provide this insight and therefore the results capture the important characteristics of uncertainty and variability of the water balance elements. Interaction with the water balance through the tool provides the means for providing greater definition of irrigation delivery and application systems, and their interaction at farm, region and valleys levels (Objective 2).

The structure of the Bayesian Network that provides the framework for the water balances at the different scales is stored in the database and can be changed to allow rapid construction of different networks to allow assessment and prioritisation of opportunities for increased WUE (Objective 3). For example, the 'whole-of-system' water balance can be constructed by aggregating the entire farm and the scheme data and an assessment of the interactions between the variables can be made. This can be compared with lower levels of aggregation at the scheme and farm scales. These results can be statistically analysed for significant differences in the response of groundwater heights and 'end of system' flows to the different farm systems and individual schemes. An example of the application of this method to the Macquarie catchment is included in Attachment 1. These results provide a probabilistic expression of the water flux interactions at farm, scheme and catchment levels, which goes some way to meeting Objective 4.

Objective 4 of the project required the quantification of potential water savings through increased farm, sub-catchment and valley-wide efficiency in the Macquarie and Murrumbidgee river valleys of NSW. In this project the unaccounted for water in the water balance was used to make an assessment of the potential water savings. Given that the methodology evolved over the life of this project and the final methodology was only applied to the Macquarie valley, the results presented in Attachment 1 focus on this valley. Some results are presented for the Murrumbidgee, but these are limited to the application of the first methodology and should be interpreted with caution (see Appendices to Attachment 2).

The Bayesian Network outputs enable the characteristics of the status of the water balance to be determined at a glance, for example the percentage of unknown values that contribute to the water balance. This provides an indication of where effort is required in order to improve the quantification of potential water savings, which is the first step required in fully meeting Objective 4.

The final objective of this project was to document the factors that influence crop planting and watering behaviour, as well as the documentation of the factors required for successful whole-of-system WUE assessment. A comprehensive literature review was conducted on crop planting and watering behaviour, which is provided as Appendix F of Attachment 2. The main finding of this review is that most studies actually report on how it is believed farmers should behave; very few report on actual behaviour.

Documentation of the factors required for successful whole-of-system WUE assessment are encapsulated in the software that was produced as the major output of the project: the WOS WB tool.

# 4 APPLICATION OF OUTPUTS

The WOS WB tool is a valuable asset for understanding the behaviour of the water balance at various scales. The value of the tool is in the rapid development of Bayesian Networks that provide a probabilistic assessment of the water balance at different scales (farm, scheme and catchment). This capability can be used as a means for focussing the discussion between catchment managers, irrigators and other stakeholders.

The WOS WB tool is transferable to other valleys and can be used to investigate the characteristics of the water balance using available and relevant data. The tool also provides an audit of the datasets that are available for assessing WUE and can be used for prioritising data collection.

# 5 SUMMARY OF COMMUNICATION, TECHNOLGOY TRANSFER AND ADOPTION ACTIVITIES

The final methodology was presented as posters at the 2005 CRC for Irrigation Futures Annual Research Forum and the ANCID conference. The previous methodologies have been presented at various forums (IAA 2002 and 2003 conferences, Northern Murray Darling Water Balance workshop 2003, Vic DPI Bayesian Network workshop 2005), monthly reports sent to a variety of interested parties and a magazine article (see publication list).

As this tool has only been recently developed there has not been an opportunity to provide a 'hands-on' demonstration to potential users. The Cotton Catchment Communities CRC has expressed an interest in investigation the potential use of the tool. The potential application of this tool was discussed at a meeting with the IAA and the National Water Commission in mid October 2005. These discussions are continuing.

# 6 POTENTIAL COMMERCIAL OPPORTUNTIES

This tool was developed in the c# programming environment with the assistance of Michael Pearson from SCOLARI SOFTWARE. The SCOLARI SOFTWARE firm developed the WATERTRACK software, which calculates a daily water balance using data collected at the farm level. There is potential for the outputs from the WATERTRACK to be integrated into the WOS WB tool and therefore provide a more rigorous assessment between the links of the water balance at the different scales. WATERTRACK is joint venture between Aquatech Consulting, SCOLARI SOFTWARE and Sustainable Soils Management and has been commercialised. If this potential were to be realised through a new project the WOS WB could be developed as a commercial tool for use by catchment managers, Food and Fibre groups and government agencies.

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Emerson, A. (2003) whole-of-system water use efficiency – what becomes of the water that does not reach its intended destination? IREC Farmers' Newsletter, Large Area Edition, No. 163, Autumn 2003.

Fairweather H. (2005) Bayesian Networks for Water Balances, poster presented at ANCID conference, Mildura, Vic, Oct 2005.

Fairweather H. (2005) Casting a Net over the Bayes to Balance the Water, poster presented at the 2005 CRC for Irrigation Futures Annual Research Forum, Mildura, Vic, Sep 2005.

Fairweather H. (2003) Determining whole-of-system Water Use Efficiencies for Selected NSW River Valleys, Northern Murray Darling Workshop 2, Narrabri, NSW.

Mitchell, D. (2002) Development of a Whole of System Approach to water use efficiency , paper presented to the 2002 IAA conference, Sydney, NSW.

*Whole-of-System WUE and Water Balance Assessment Analyses.*

**Attachment 1 to Determining whole-of-system Water Use Efficiency (DAN 14) Final Report for the National Program for Sustainable Irrigation (Land and Water, Australia)**

Helen Fairweather, 1st November 2005

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# 1 Introduction

Increasing the efficiency of water use requires an understanding of the underlying water balance at the scale of interest. This first objective of this project was to improve the understanding of the whole-of-system water balance, as applied to a particular valley. This has been achieved through the characterisation of the factors that influence the water balance using a Bayesian Network technique. This technique characterises the water balance in terms of probabilities of each element being in a particular state (eg. in the low, medium or high tercile) given the probabilities of other variables being in particular states. The whole-of-system water balance section (Section 2.2) of this report provides an overview of this technique and analyses.

The Bayesian Network technique has been captured in a whole-of-system Water Balance (WOS WB) tool that enables rapid development of the representation of the water balance based on the user's perspective and available data. The second objective of this project was to provide greater definition of irrigation delivery and application systems, and their interaction at farm, region and valleys levels. Interaction with the water balance through the tool provides the means for achieving this greater definition, but insufficient data were available to enable rigorous analyses within the scope of this project. Elements of the work conducted for this project to meet this objective are presented in Attachment 2 of this report.

Assessment and prioritisation of opportunities for increased water use efficiency and the quantification of potential water savings through increased farm, sub catchment and valley wide efficiency in selected valleys were also required objectives of this project. The availability of data to conduct this assessment and prioritisation was again an obstacle to fully achieving this objective. However, the limited amount that was collated did provide a snapshot of the WUE at each of the farm, scheme and valley scales. This analysis is presented in the Section 2.2 of this report.

The final objective of this project was to document the factors that influence crop planting and watering behaviour, as well as the documentation of the factors required for successful whole-of-system WUE assessment. A comprehensive literature review was conducted on crop planting and watering behaviour and is provided as Appendix F of Attachment 2 of this report.

# 2 Methodology

## *2.1 Water Use Efficiency*

Determining water use efficiency at a range of scales is data intensive and usually requires an intensive data collection exercise. However, the resources available for this project limited this collection phase to a desktop study. The datasets collated come from various sources, are of varying lengths and there are many time steps (both irregular and regular) associated with their collection. These disparate datasets led to the development of a probability based methodology to assess water use efficiency at the range of scales. This method characterises the water use efficiency at each scale in the form of probability distributions of each of the elements of the water balance.

### 2.1.1 Whole-of-System Scale

At the whole-of-system scale, the assessment of water use efficiency can be defined in very broad terms as a ratio of the accounted for water (water used for irrigation and measured end of system flows) to the total water flowing into the system (dam releases + gauged tributary inflows).

### 2.1.2 Scheme Scale

The efficiency of irrigation schemes are commonly assessed as the ratio of the water delivered at the farm gate to the total water diverted for irrigation (Barrett et al. 1999). This is essentially a measure of the efficiency of the conveyance system and accounts for the losses through seepage and evaporation from the supply channels.

### 2.1.3 Farm Scale

Water Use Efficiency at the farm scale can be assessed on individual elements of the irrigation system (eg. the application system, the plant-soil interactions and the distribution and storages structures) or an aggregation of all of these elements (eg. a whole farm). The time scales for a WUE assessment at the farm scale can vary from an event basis through to a seasonal or annual assessment for each or all of the elements.

The lack of data on the water balance at the farm scale makes it very difficult to conduct analyses of water use efficiency over this scale. This project undertook several modelling exercises in an attempt to overcome this limitation, but without a rigorous calibration exercise these results are open to question. Therefore the key message is that the first step to improving WUE at the farm scale is to measure the water balance on all the elements (eg. field, distribution, storage and whole farm).

The water balance is the fundamental building block for assessing WUE at any scale and therefore the remainder of the project concentrated on developing an understanding of its various elements at a range of spatial and temporal scales. This understanding was developed through the construction of the WOS WB tool and associated database.

## *2.2 Whole-of-System Water Balance (WOS WB) Tool*

A description of the elements that provides the structure of the water balance is required prior to the collection of the data of each of the elements of that water balance. There are both spatial and temporal attributes that describe the elements of the water balance. The spatial attributes used in the WOS WB are the latitude and longitude that defines the centre of the point of interest (e.g. climate data at a particular location) and if required an area dimension (eg. irrigation scheme areas). The variability (temporal attribute) of the water balance is described by the time series of data for each of the elements. The WOS WB is able to aggregate both the spatial and temporal attributes of the underlying data at, and between, each of the scales. The aggregations vary as a function of the time steps and lengths of the datasets.

The WOS WB tool was developed to describe the probabilities associated with the flux of water between the scales. This approach is novel in its coupling of disparate datasets and the use Bayesian Networks as the means of representing the water balance. The Bayesian Networks, built in Netica (Norsys software corp. 1997), provide a method to represent relationships between variables even if relationships involve uncertainty, unpredictability or imprecision. Links between variables can be established deterministically or probabilistically by observation or expert opinion. The user of the WOS WB tool is able to represent the water balance of at a particular scale based on their understanding of the linkages and the available data.

The links that join the elements of the water balance are used to calculate probabilities of each of the elements being in a certain state, conditioned on the state of the linked variables. These probabilities are based on the underlying time series data that has been used to populate the database associated with a particular scale.
One of the states that can be assigned to an element of the water balance is ‘unknown’. The inclusion of this ‘unknown’ characteristic in the WOS WB tool provides the user with a comprehensive overview of the status of data collection for a particular valley. This is an important outcome in terms of prioritising the collection of data into the future.

# 3 Results

## *3.1 Whole-of-System Scale*

Data used for the assessment at the whole-of-system scale were only available over a period of eight years and were collected from a variety of sources. The 1998-00 end of system flows were obtained from the relevant

DLWC annual reports (see Mitchell (2002)) (Table 1). Dam releases data for 1993-98 were obtained from State Water database (D Barnes pers comm). The dam releases for 1998-00 and the gauged tributaries were obtained from DLWC annual reports (see Mitchell (2002)) (Table 2). The volume of water diverted for use was obtained from Macquarie Valley Irrigation Profile (Hope 2002) (Table 2). End of system flows (Table 2) were obtained from State Water database (D Barnes pers. comm.) for the years 1993 to 1998.

**Table 1. Assessment of whole-of-system efficiency for Macquarie Valley.**

| Year | Dam releases and gauged tributaries (GL) | Irrigation and end of system flows (GL) | whole-of-system Efficiency |
|---|---|---|---|
| 1993-94 | 941 | 636 | 68% |
| 1994-95 | 820 | 537 | 65% |
| 1995-96 | 338 | 281 | 83% |
| 1996-97 | 687 | 390 | 57% |
| 1997-98 | 626 | 409 | 65% |
| 1998-99 | 1987 | 1876 | 94% |
| 1999-00 | 1094 | 736 | 67% |
| 2000-01 | 1784 | 1084 | 61% |
| Median | 880 | 587 | 67% |

This assessment demonstrates the great variation in the calculated whole-of-system efficiencies, which range from 57% to 94% (Table 1). The year in which the high efficiency of 94% was calculated coincided with a relatively high rainfall year (considered in the same eight year period) and the lowest evapotranspiration (ETo) and evaporation (Figure 1) averaged from the SILO datadrill on a 5km grid (BoM 2005). The next highest whole-of-system efficiency occurs in a year when the dam releases and gauged tributary inflows were the lowest in the eight years of record (Table 1). The climate data averaged over the catchment for the entire record (rainfall = 524 mm; evapotranspiration = 1396 mm; evaporation = 1802 mm) suggest this was an average year. Without these two relatively high values, for the rest of the record the whole-of-system efficiency ranges between 57% and 68%.

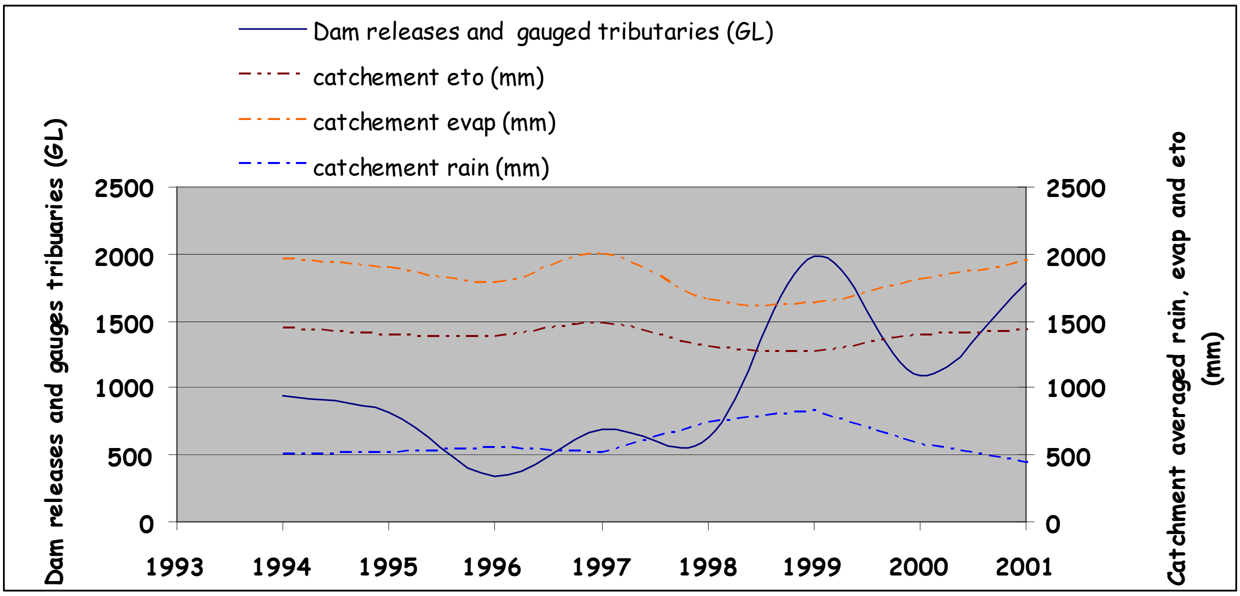


**Figure 1. Annual average climate data (BoM 2005) compared to total dam releases and gauged tributary inflows (GL).**

## 3.2 Scheme Scale

There were only sufficient data to apply this calculation for two schemes within the Macquarie Valley (Narromine and Tenandra) and only for six and eight years for each scheme, respectively (Table 2) (See attachment 2 for details on these two schemes).

With the exception of one year for the Narromine Irrigation Scheme, the conveyance efficiency for both these schemes ranges between 80% and 86%. The exception occurred in 1995-96 water year, when the conveyance efficiency was calculated to be 62 %. This corresponds with the year when a relatively high efficiency was calculated at the whole-of-system scale (Table 1), suggesting the losses from the scheme scale did not translate to a loss at the whole-of-system scale.

**Table 2. Conveyance Efficiency for the Narromine Irrigation Scheme (Narromine Irrigation Board of Management 2001) and the Tenandra Irrigation Scheme (Lyn Davies, pers comm.)**

| Year | Diversion/River pump (ML) | Farm Deliveries (ML) | Conveyance Efficiency |
|---|---|---|---|
| **Narromine Irrigation Scheme** | | | |
| 1994-5 | 50407 | 41362 | 82% |
| 1995-6 | 17095 | 10614 | 62% |
| 1996-7 | 35093 | 28093 | 80% |
| 1997-8 | 24047 | 19850 | 83% |
| 1998-9 | 33145 | 28150 | 85% |
| 1999-00 | 43072 | 36900 | 86% |
| Median | 34119 | 28122 | 82% |
| **Tenandra Irrigation Scheme** | | | |
| 1995-6 | 12000 | 9840 | 82% |
| 1996-7 | 24000 | 20400 | 85% |
| 1997-8 | 31000 | 26350 | 85% |
| 1998-9 | 21108 | 17731 | 84% |
| 1999-00 | 28941 | 24021 | 83% |
| 2000-01 | 40633 | 33725 | 83% |
| 2001-02 | 42366 | 35164 | 83% |
| 2002-03 | 22536 | 18480 | 82% |
| Median | 26471 | 22211 | 83% |

## 3.3 Farm Scale

However a previous project conducted in the Macquarie valley "Measure Water to Manage Water" (Swann et al. 2002) measured efficiencies and distribution uniformities on furrow irrigated cotton crops on an event basis over a range of soil types. This project found that the majority of application efficiencies were below 50%, with the majority of distribution uniformities around 60-80%. These limited results indicate there is considerable room for improvement at the irrigation application level.

## 3.4 Whole-of-System Water Balance (WOS WB) Tool Applied to the Macquarie Valley

Numerous sources were used in assembling data for the whole-of-system water balance. A summary of the data required to populate the WOS WB tool is provided in Table 3. For a complete description of all the datasets and associated references see Attachments 1 and 2.

**Table 3. Data requirements of the WOS WB tool (Ca = Catchment; Sc = Scheme; F = Farm).**

| Scale | Variable | Attribute | Dimension | Comment |
|---|---|---|---|---|
| Ca | Total dam diversions | Annual | Volume (ML) | All annual data is aligned to the July to June water year. For the Macquarie Valley there were insufficient data for the total and irrigation diversions from the dam on an annual basis, and the individual scheme diversion data. Therefore these time series were removed from the water balance analyses. However, they were considered in a WUE analyses across the various scales. |
| | Tributary inflows | | | |
| Ca/Sc | Irrigation diversions | | | |
| Ca/Sc/F | Evaporation | Daily to Annual | Depth (mm) | Daily climate data is used at the farm scale and aggregated from 5km grid points defined by the water balance boundaries for the other scales. |
| | Evapotranspiration | | | |
| | Rainfall | | | |
| | Location | Lat/long | | Climate points are used to store the location of the climate data, scheme centres and representative farms. |
| Ca/ F | Groundwater depths | Irregular | Depth (m) | At the farm scale the groundwater sampling interval governs the temporal scales of the water balance. |

The whole-of-system water balance requires the aggregation of the collected data for various spatial and temporal scales. A spatial representation of the aggregated data collection is possible through the interface of the WOS WB tool (Figure 2). This graphical output relies on the spatial attributes associated with each dataset being entered into the database. Each of the schemes is represented by a circle with the relative area represented by the size of the circle. The circle representing each scheme is centred on its estimated mid point, with riparian irrigators represented by a single scheme centred on the estimated mid point of the whole area under consideration (Figure 2).

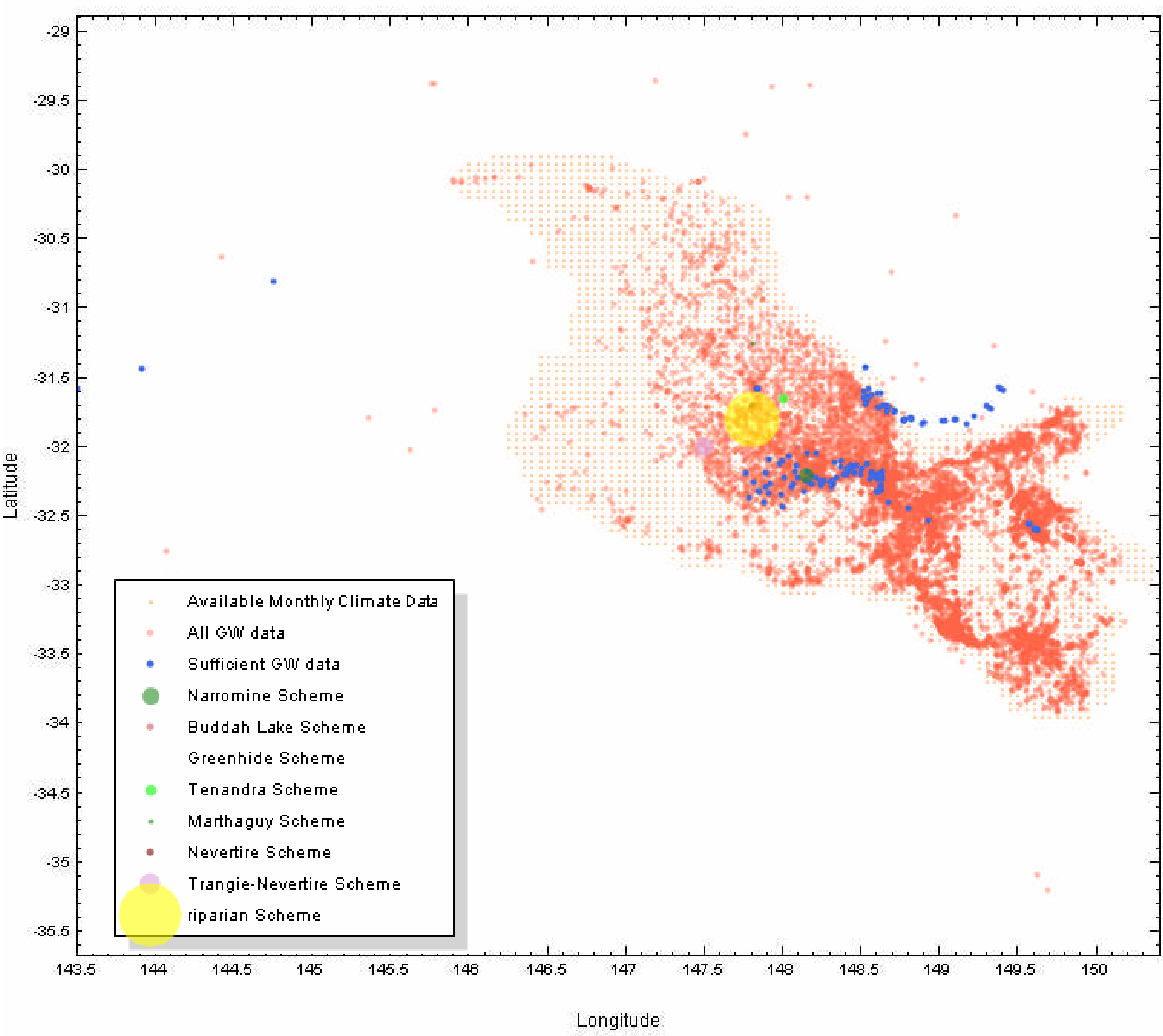


**Figure 2. Spatial representation of data included in the whole-of-system water balance analsyes for the Macquarie Valley.**

The software interrogates each of the aggregated elements in the water balance and determines the tercile boundaries for all except groundwater. These boundaries are used by the software to translate the result to a qualitative measure (low, medium, high and unknown) for the required time step (annual for the whole-of-system). For groundwater, the boundaries for rising, falling and static levels are arbitrarily set by the user and a similar qualitative transformation is applied.

The qualitative measures are then used to construct the Bayesian Network and associated conditional probability tables (CPTs) (see Appendix B to Attachment 2 for a description of how the network is linked by the CPTs), which is a reflection of the users understanding of the flux of water through the system. These networks can be opened using the Netica® software (Norsys 1997).

Bayesian Networks require *prior*[1] probabilities as input, which are derived from the structure of the network and conditional probabilities and calculated in the WOS WB tool. The Netica® (Norsys 1998) software uses a *probabilistic inference*[2] technique to establish the *posterior*[3] probabilities relating to a particular configuration selected by the user.

The whole-of-system water balance for the Macquarie valley was developed based on the author's understanding of the flux of water through the system (Figure 3) given the available data, which were rain and evapotranspiration (averaged over the catchment and also averaged over the scheme locations (farm level)), tributary inflows, average groundwater changes over the year, and a defined end of system point at Carinda.

For the variables in the water balance framework constructed for the Macquarie Valley that are 'independent' (ie. catchment and farm rain and ETo) (Figure 3), their compiled *prior* distribution is uniform (ie. equal chance of being in each of the terciles). These 'independent' variables are termed parents. However the *prior* probabilities for the variables believed to be influenced by these independent variables (ie. Tributary inflows (Trib), groundwater change (gwchange) and end of system flows (EOS)) (Figure 3), are conditional on the behaviour of their parents.

The groundwater change for the annual time step is calculated in the WOS WB database and is restricted to bores that have at least seven months between the first and last measurement for any given water year. The average of these changes is then aggregated for each year.

Therefore the Bayesian Network constructed for the Macquarie valley based on ~100 years of annual data suggest that for a large proportion of the time the groundwater change and end of system flows are unknown (52% and 44% respectively) (Figure 3). If these variables were considered without the influence of their 'parents' they would exhibit a uniform distribution for the remainder of their states (e.g. low, medium, high for EOS; rising, static, falling for groundwater change). It is the influence of all the variables that are linked (either directly or through an intermediate variable) that govern the *prior* probability distribution determined by the Netica® software (Norsys 1997).

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[1] *Prior* probabilities are the probabilities before any findings are entered

[2] *Probabilistic inference* is the process of calculating new beliefs for a set of variables, given some findings.

[3] *Posterior* probabilities are the final beliefs given the entered findings.

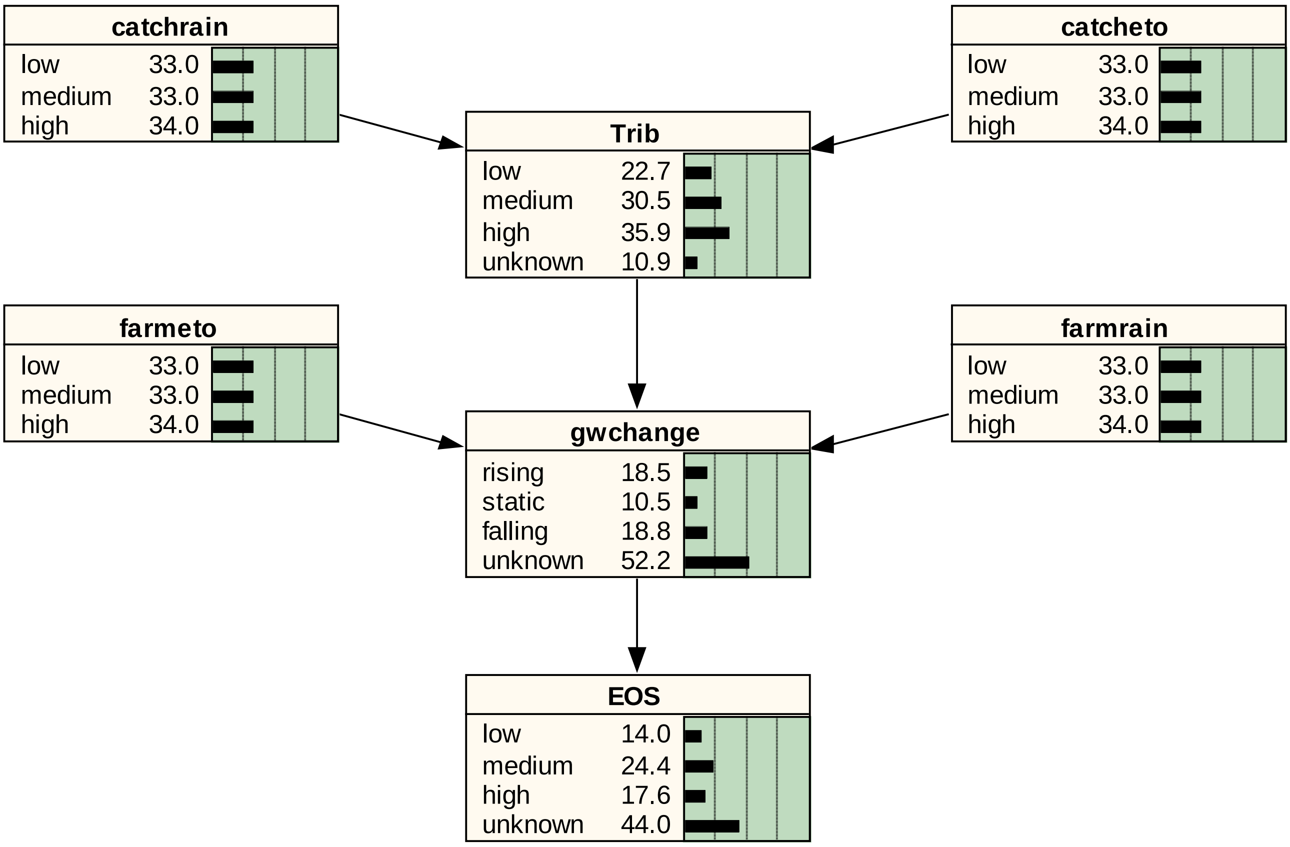


**Figure 3. Whole-of-System Water Balance using Bayesian Networks showing the *prior* probability distributions. The *prior* probabilities for the variables believed to be influenced by these independent variables (ie. Tributary inflows (Trib), groundwater change (gwchange) and end of system flows (EOS)) (Figure 3), are conditional on the behaviour of their parents (catchment and farm rain and ETo).**

The annual rain and evapotranspiration data at the catchment scale (catchrain and catcheto in Figure 3) were averaged from monthly data for 3303 points at 5km intervals using the boundaries of the catchment from the Burrendong dam to the end of system flow measuring point (Carinda) as the boundaries for the grid. These data were sourced from SILO Data Drill (BoM 2005) and the annual averages were based on the water year (July to June). Because of the volume of data required, this analysis is conducted externally to the WOS WB database and imported in the required format (ie. annual averaged data aligned to the water year).

In analyses conducted previously in this project and presented in Attachment 2 and associated Appendices, the modelled total and irrigation diversion data from the Burrendong dam were included. These data were supplied by IQQM (DLWC 1995) modelling based on the 1994 development levels and as such do not provide a realistic dataset for undertaking the analyses being conducted for this project. Therefore only the end of system flows at Carinda and the tributary inflows obtained from the State Water database (D Barnes pers comm) and annual reports (see Mitchell (2002)) were used for the water balance assessment.

The groundwater data were obtained from the dataset maintained by the NSW Department of Natural Resources (DNR 2000). This database contains approximately 48,000 records for 1,338 bore sites with the number of records associated with each bore ranging from 1 to 445. Of the total records only ~5% are for the period prior to the construction of the Burrendong dam and most of the irrigation development in the Macquarie Valley. The dataset that is currently in the WOS WB database extends to December 2002. Therefore the majority of analyses of groundwater are constrained to the time irrigation commenced, making it difficult to draw any inference about the impact of irrigation on groundwater levels.

The behaviour of the constructed water balance can be investigated by entering 'findings' for one or more variables. The probability distributions that are calculated after a 'finding' has been entered are the *posterior* distributions.

With the limited amount of data included in the whole-of-system water balance it is important not to 'drill' down too far by entering 'findings' for too many variables as the results that are produced may be based on only one or a few cases. For example, the change in groundwater is observed to be static 25% of time, falling 25% of time and unknown 50% of time when farm rainfall is in the medium tercile, the farm $ET_o$ is in the high tercile and the tributary inflows are in the high tercile (Figure 4). However there is only one record in the dataset that matches this configuration for a static groundwater change, one record for falling groundwater and two for unknown, hence the *posterior* probability distribution for this configuration is based on only four records. Obviously this is insufficient data from which to derive any sensible conclusion for this configuration of findings. At this stage, the user needs to interrogate the database to determine the number of data points that are being used in the selected analysis. Further development of the WOS WB could include an indication of the number of records being used to produce the conditional probabilities in each category.

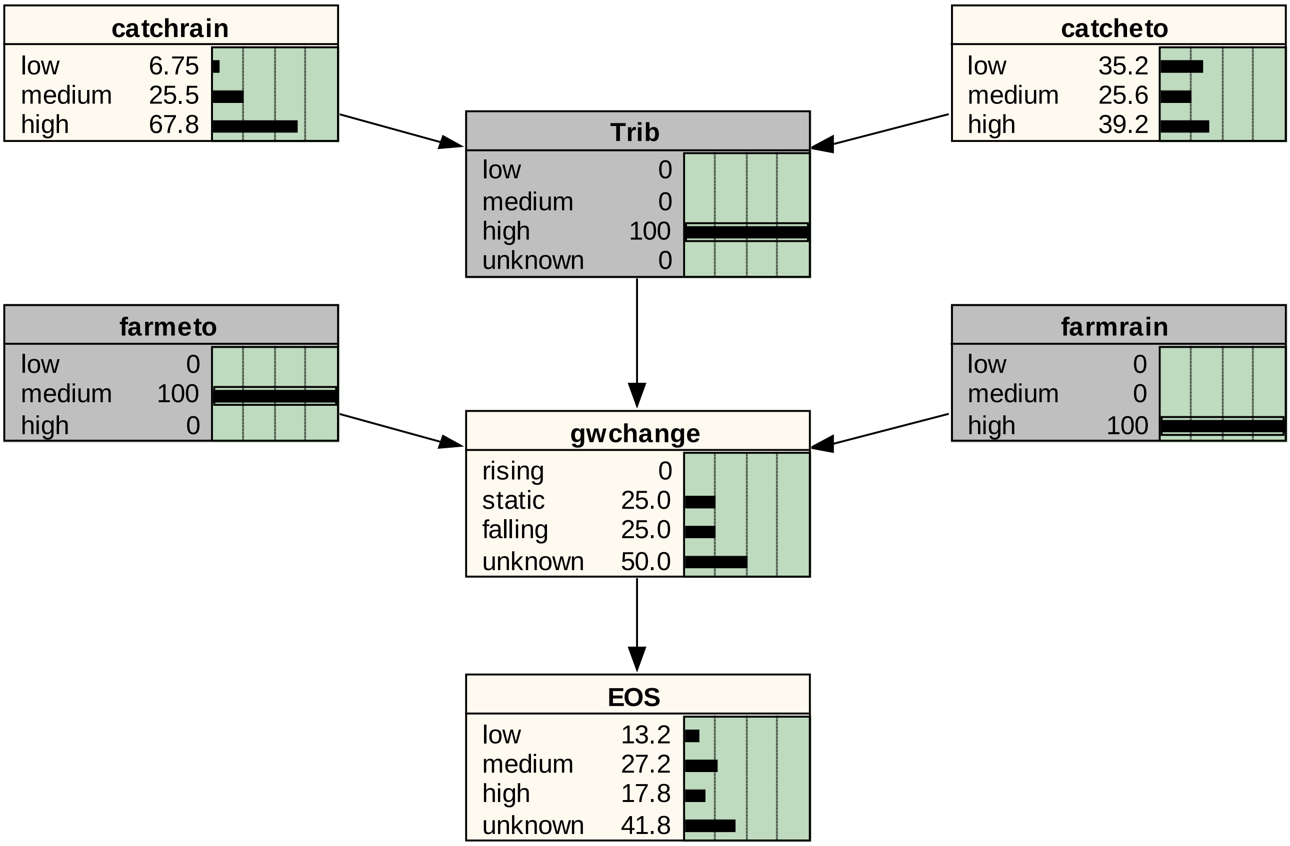


**Figure 4. Example of 'findings' entered for Farm ETo (farmeto), farm rain (farmrain) and Tributary inflows (Trib).**

The results shown in Figure 4 also demonstrate the two-way propagation of probabilities in the network. For example, when a finding of 'high' is entered for the Tributary inflows, the probability distribution of its parents change (Catchment rain and ETo). In this example it can be easily seen that there is a much higher change of a high catchment rainfall (68%) being associated with high tributary inflows compared with a high catchment ETo (40%). When 'low' and 'medium' findings are entered for tributary inflows there is a corresponding shift in probabilities for catchment rain (not shown) suggesting a linear relationship. Statistically this relationship is not strong with an $r^2$ of only 0.4 (Figure 5), however because the Bayesian Network relies on probabilities the statistical strength of the relationship is not an important factor.

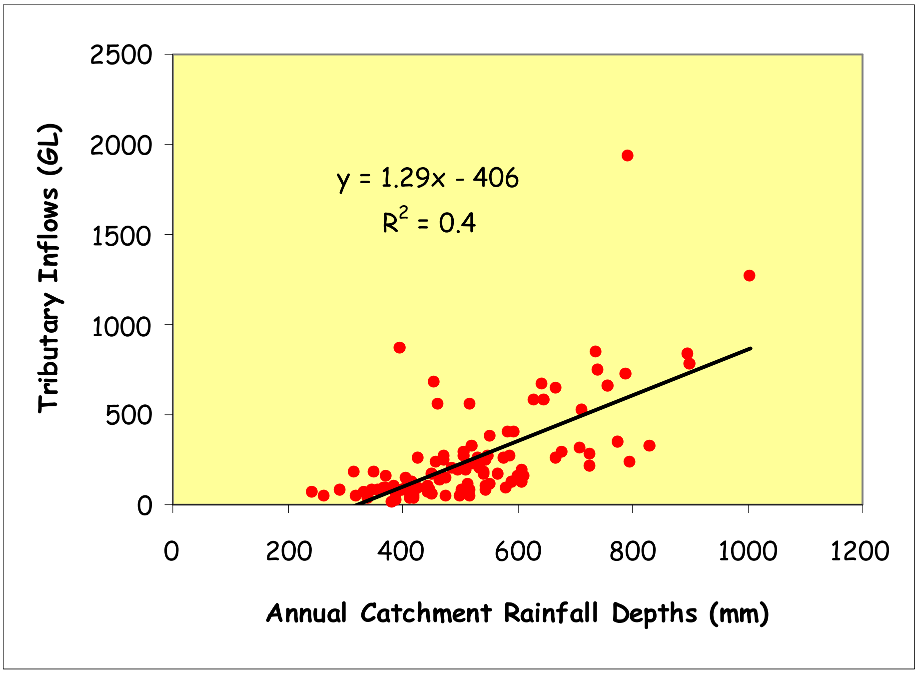


**Figure 5. Relationship between annual tributary inflows and rainfall aggregated across the catchment.**

### 3.4.1 Introducing More Variables

The objective of developing the whole-of-system water balance is to combine disparate data available through various agencies, local knowledge and modelling to provide insight into how irrigation can impact on the water balance at different scales. The lack of data to undertake this assessment is a constraint to drawing any rigorous conclusions from the above analysis, apart from establishing the overall characteristics of the water balance in a probabilistic and qualitative sense. In the ideal world, the data used for this analysis would include the areas irrigated for each commodity group, yields and the actual water applied. For most of the schemes in the Macquarie valley the cotton is the majority crop grown, with wheat in rotation (Table 4). Therefore, the above analysis may be enhanced by the inclusion of data relating to this system.

**Table 4. Average percentage area grown for each crop class in the Macquarie valley (from data compiled for the Macquarie profile (Hope 2004)).**

| Crop Class | Average percentage area grown |
|---|---|
| Annual Pasture | 4% |
| Citrus | 1% |
| Cotton | 62% |
| Lucerne | 7% |
| Orchards | 1% |
| Perennial Pasture | 1% |
| Pulses | 1% |
| Summer Oilseeds | 5% |
| Summer Cereals | 5% |
| Vegetables | 1% |
| Vines | 1% |
| Winter Cereals | 10% |
| Winter Oilseeds | 1% |

The Macquarie irrigation profile (Hope 2004) compiled 12 years of the area of irrigated cotton from 1989 to 2000. This is insufficient data to include in these analyses; however the ABS does provide historical analyses of several commodities (including wheat) and reports on annual area grown and yield since 1861 for these variables. An investigation of the relationship between the NSW wheat yields and area grown to cotton for the Macquarie for the corresponding 12 years between 1989 to 2000, indicates a general trend ($r^2 = 0.6$) in the relationship between these two variables (Figure 6).

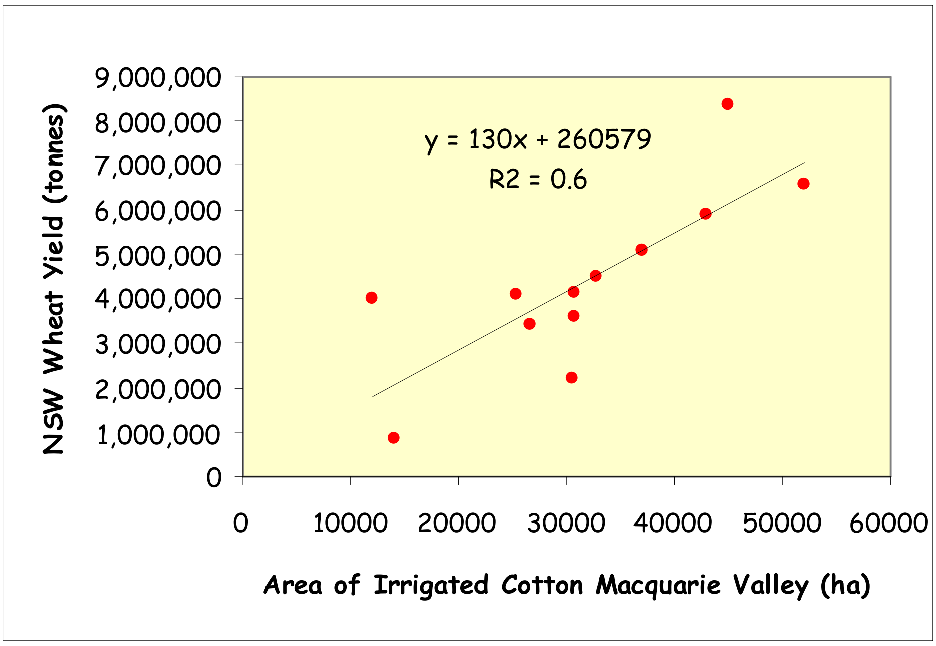


**Figure 6. Relationship between NSW wheat yields reported by ABS (2005) and area of irrigated cotton in the Macquarie Valley (Hope 2004).**

The errors associated with extrapolating the above relationship out to ~100 years of data are unknown, however for the purposes of illustrating the inclusion of other variables that are indirectly associated with the water flux, the following analysis includes the NSW wheat yields in the 'water balance' framework. The inclusion of wheat yields in the Bayesian Network has very little impact on the probability distributions for groundwater change and end of systems (Figure 7).

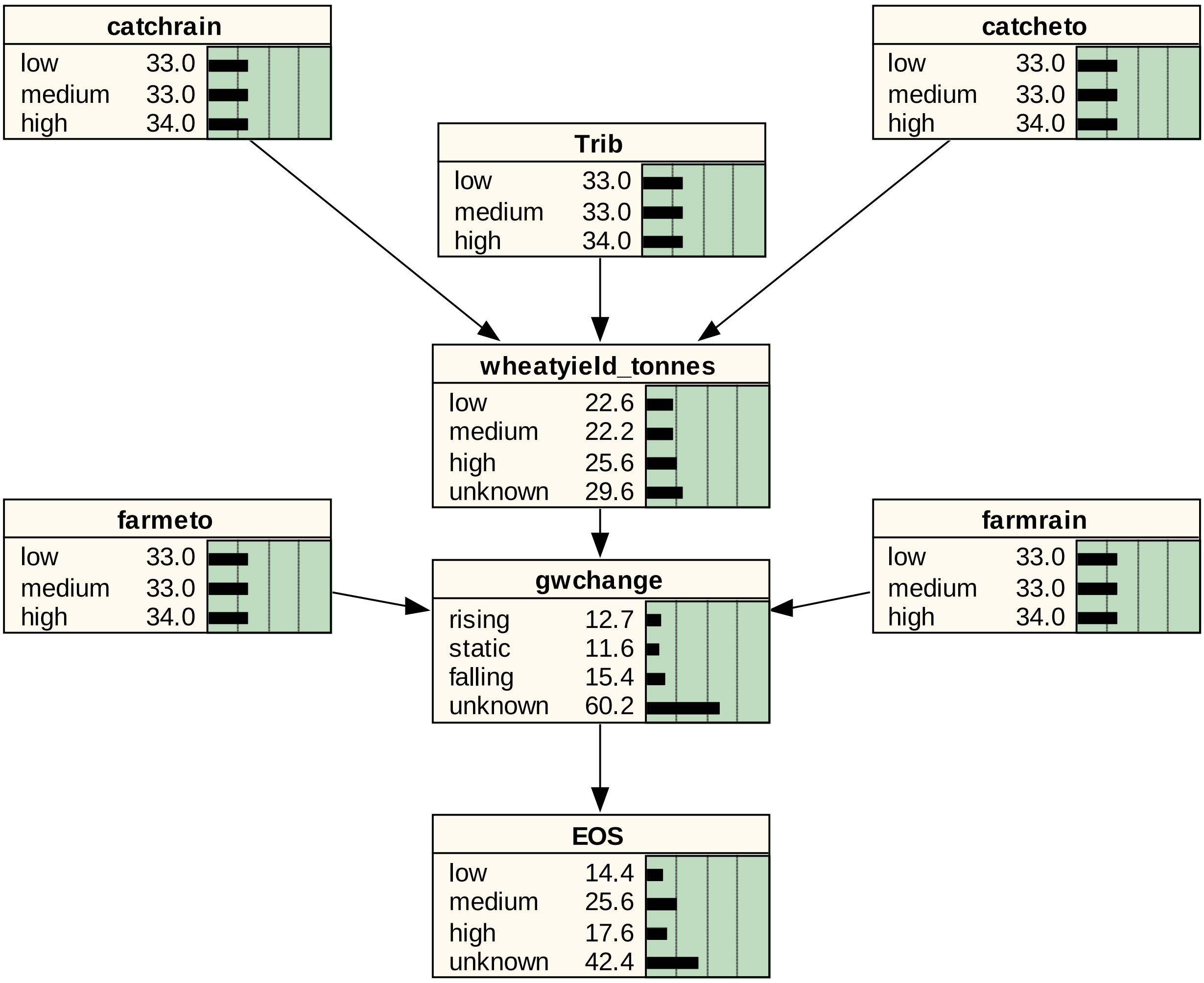


**Figure 7. Bayesian Network including wheat yield data**

Because there isn't a full record for groundwater change or EOS there is a high percentage of unknowns in the Bayesian Networks when the *prior* probabilities are considered. However the *posterior* probabilities for a finding of 'high' wheat yields indicates a very different distribution, with the 'unknown' probability for groundwater change falling to 20% (not shown).

The reason for the large impact of high wheat yields on the distribution of groundwater levels is that they have generally increased over time (Figure 8) and the majority the annual groundwater level changes are found in the last 30 years of data (Figure 9).

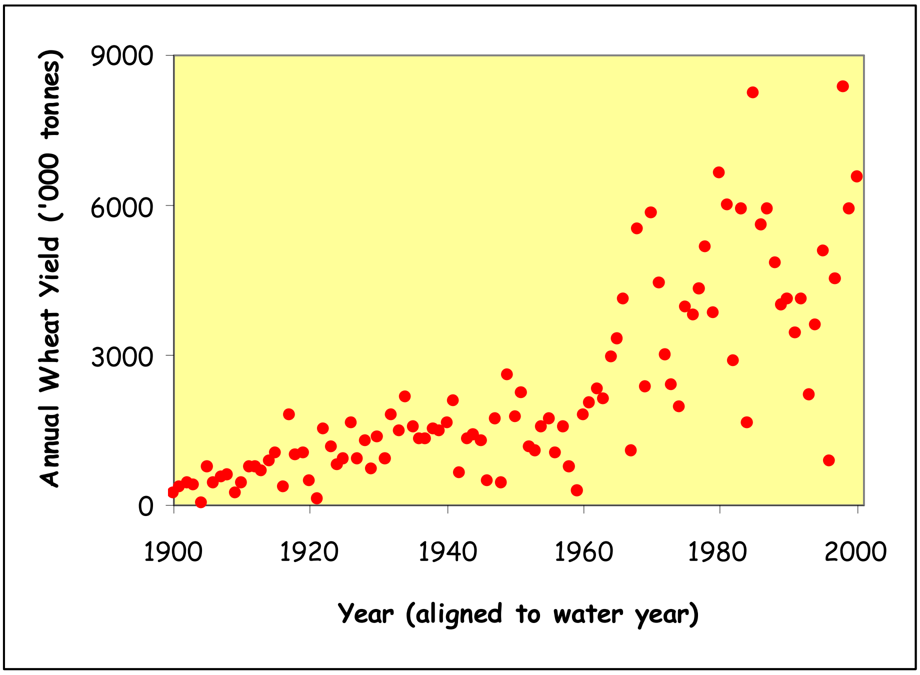


**Figure 8. Annual Wheat Yields for NSW (ABS 2005)**

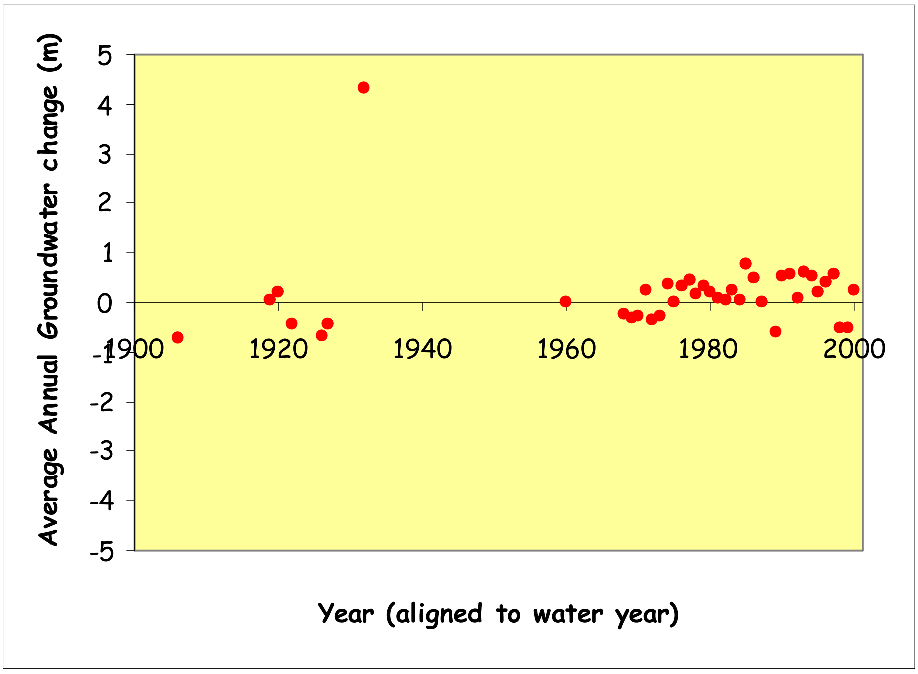


**Figure 9. Average Annual Groundwater change (m) (positive change = falling groundwater level) (calculated from SWL database (DNR 2000))**

### 3.4.2 Link Between Scales

As well as the whole-of-system scale analyses at an annual time step, the WOS WB tool also has provision for analysis at a specific site. Groundwater level data provide the link for conducting this analysis. However, there are over 100 bores that are considered to have sufficient data to be included in the analysis and assessing which dataset to include is not a trivial exercise. An investigation of the behaviour of the bores was undertaken to narrow down the dataset for analysis.

An investigation of the rate of change of groundwater levels can provide some indication of where to focus further analysis. The WOS WB tool interrogates the database of Standing Water Levels for all the groundwater bores included in the groundwater monitoring dataset (DNR 2000). To filter out bores that have been sampled irregularly a constraint was applied to those bores that have an average sampling interval of less than seven months. This restricted the record for analyses to ~120 bores (see Figure 2).

When the model is 'run' the change of groundwater level and the number of days over which the change occurred are calculated for each of the records for each of these bores. For the case of the Macquarie this resulted in approximately 17,000 records. By aggregating the average rate of change of the Groundwater level (change in groundwater level/number of days for each change) for each of these bores and graphing the results it can be determined if there are any geographical areas that are exhibiting similar behaviour.

It is evident from this analysis that there are a couple of groupings of bores that exhibit a generally rising groundwater level (positive change) around the latitudes of -32.25 and -31.75 and a longitude around 148. A similar grouping can be observed for falling groundwater levels (negative change) (Figure 10). This information is important for focusing further investigation of the behaviour of the water balance at different scales.

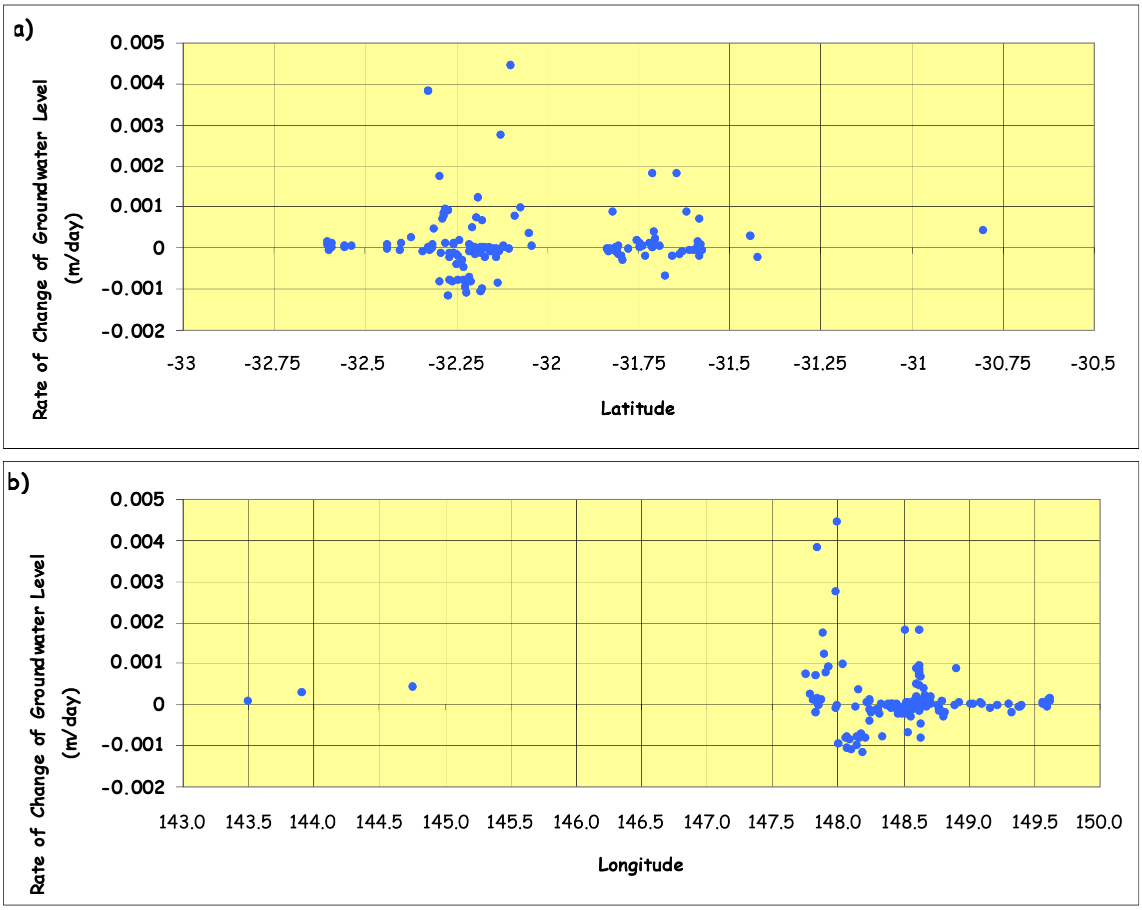


**Figure 10. Average rate of change of groundwater levels plotted against latitude (a) and Longitude (b)**

Queries have been set up in the WOS WB database to automatically extract data required for this rate of change of groundwater level analysis. Another query extracts data for the bores that exhibit the most rapidly changing behaviour (ie. rate of change > 0.1 m/day and < -0.1 m/day). The location of these bores are graphed in relation to the location of the schemes (Figure 11).

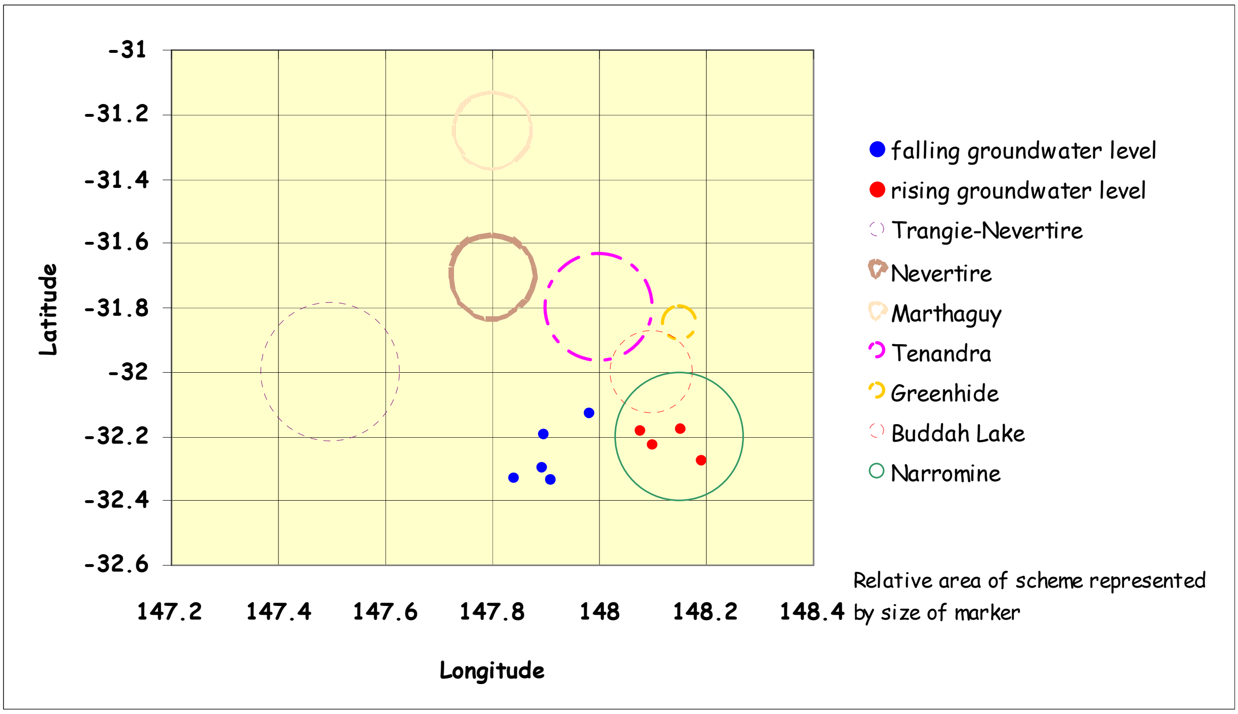


**Figure 11. Location of falling and rising groundwater levels in relation to location of schemes in the Macquarie Valley.**

The time series for each of these identified bores can also be extracted from the database and graphed in order to pinpoint a more focused analysis (Figure 12). All the groundwater bores that were assessed as exhibiting a rising trend are confirmed in this time series graph. However, only one of these bores continued sampling after the mid nineties and the rising tend does not continue. After this time it exhibits more variable behaviour without an increasing or decreasing trend. The bores that were assessed as exhibiting a falling groundwater trend based on a rate of change calculation also followed the pattern of the rising bore up until a similar point of time in the mid nineties, when there was a sudden drop followed by a far greater variability.

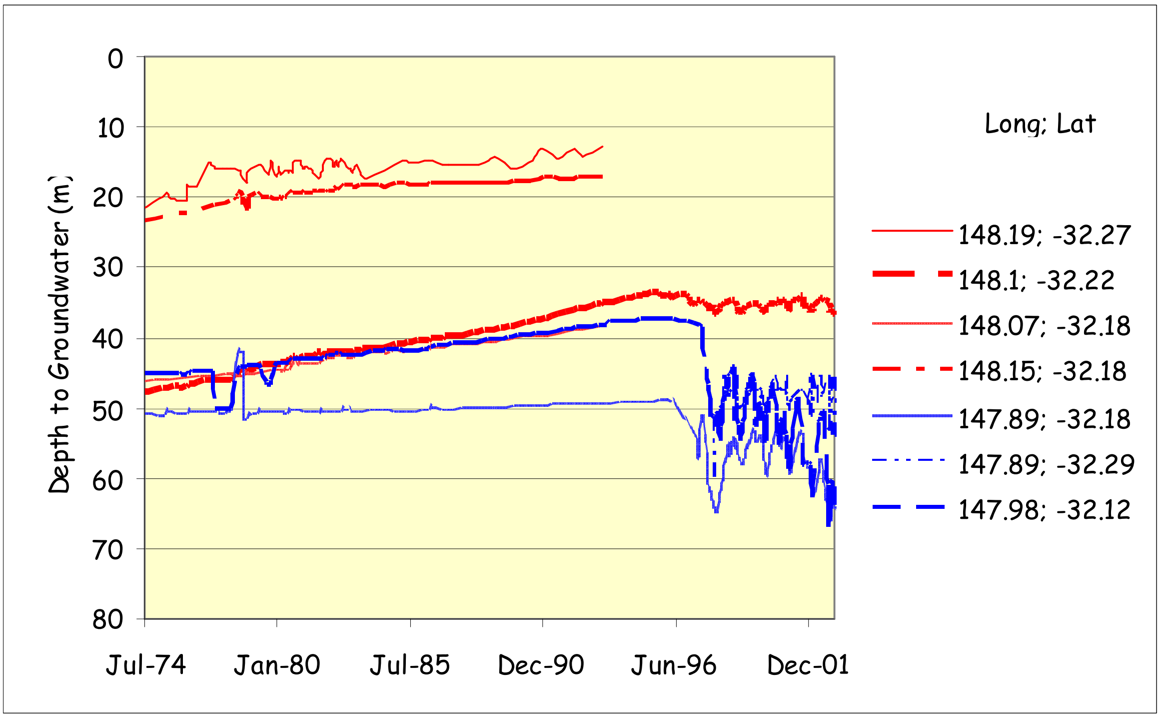


**Figure 12. Time series of depth to groundwater for selected bores.**

Analyses can be conducted across the catchment using a variety of criteria to limit the bores for further investigation. For example, the sum of groundwater change, as opposed to the average change of groundwater, indicates the bores that are exhibiting a rising or falling trend over time. This can be further related to the depths of the completed bores (Figure 13) and the dataset for analyses can be restricted to bores of different depths that are close together (Figure 14). These further analyses were not conducted for this project, due to the lack of a sufficiently large dataset. However, over the coming months as the tool is trialled, it is hoped that more data will become available to enable these further analyses.

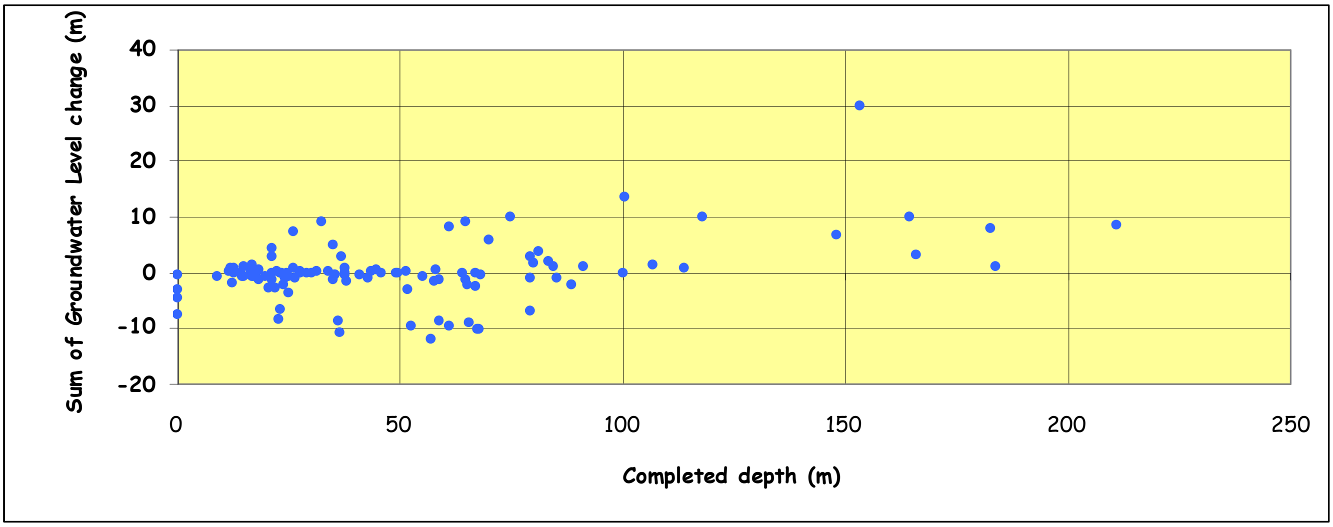


**Figure 13. Sum of groundwater level changes as a function of depth of bore.**

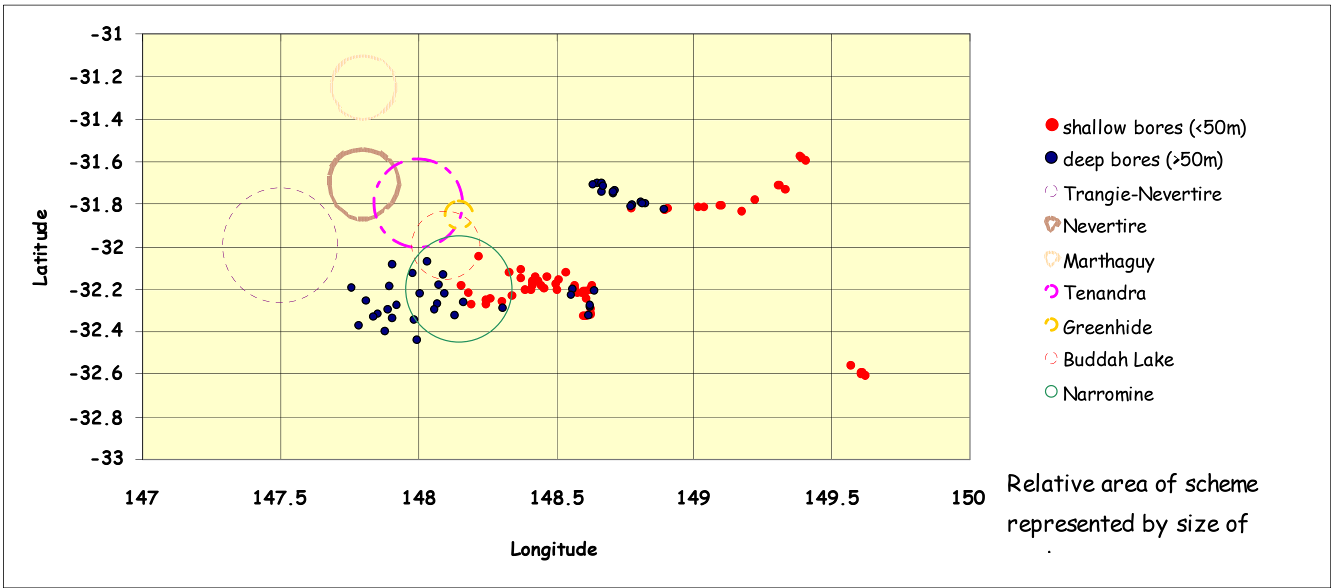


**Figure 14. Location of deep and shallow bores in relation to location of schemes in the Macquarie Valley.**

### 3.4.3 Farm Scale

In the WOS WB tool, a bore is associated with a particular farm and the characteristics of the bore can be captured as a function of the local scale climate or irrigation applications (if modelling or actual data are available). In this case the conditional probability tables are governed by the number of days between sampling for the particular bore chosen. The change in groundwater level of the sampling times is matched with the sum of rainfall, $ET_o$, irrigation applications (if available) and other variables of interest that the user might wish to investigate.

These data are then used to develop the conditional probability tables for the Bayesian Network representing the farm scale (Figure 15). In this representation of the farm scale water balance, total $ET_o$ and total rainfall are conditioned (ie. conditional probabilities are calculated) on the number of days between sampling points (NumDays). The change in ground water is then conditioned on the probabilities of total $ET_o$ and total rainfall being in the low, medium and high tercile for that sampling period.

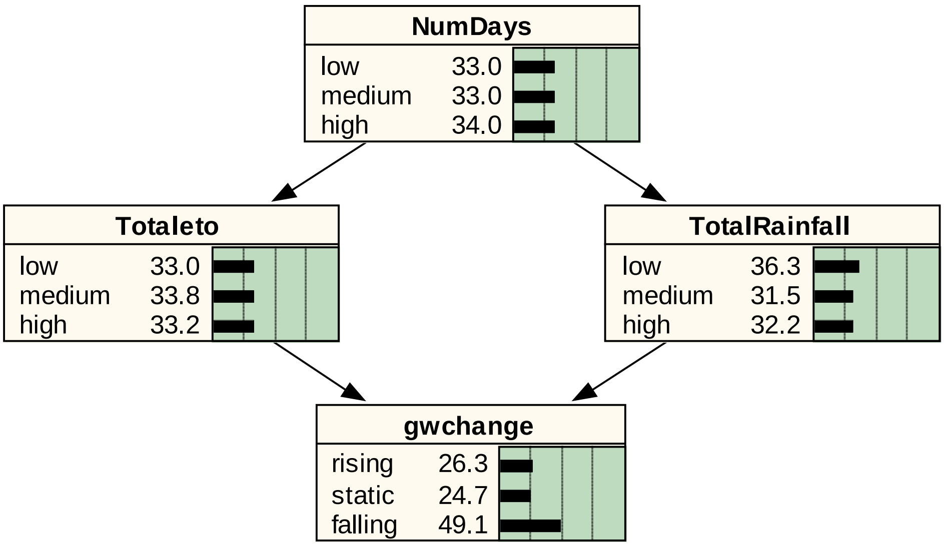


**Figure 15. Bayesian Network representation of the farm scale water balance.**

There are many examples of how the farm scale water balance can be configured (ie. aggregating a number of adjacent bores and looking at the sum of groundwater change rather than the average) and their usefulness is most likely to be as a tool for understanding the behaviour of a particular bore and a nearby farming system. Given the limited data currently in the database at the farm scale and the many configurations that are possible, it is not practical to present further analyses of the farm scale water balance for this report.

With further farm scale data the WOS WB tool could be used to facilitate discussion between irrigators and organisations that have responsibility for managing the resource (eg. CMA's and State Water in NSW).

# 4 Conclusions

This project has explored the possibility of assessing water use efficiency at the whole-of-system scale. The initial methodology developed for this project was based on the traditional water balance, which requires that each element in the water balance be dimensionally equivalent. These traditional water balances were applied at the farm, scheme and catchment scales.

The assessment of water use efficiency at any scale is a data intensive exercise, which is generally difficult to obtain. Data that are available are generally held in different locations and there are different time steps associated with each dataset, making it difficult to align them. The methodology developed in this project provides a means of bringing these disparate datasets together, and adopts an assessment based on probabilities of outcomes in a qualitative sense.

The WOS WB tool, coupled with an associated database and the Bayesian Network technology, enables a qualitative investigation of the water balance in terms of probabilities of being in certain states given that variables that are believed to have an influence are in known states.

The methodology of coupling the disparate datasets and using Bayesian Networks as the means of representing the water balance is novel in that the focus is on the flux of water between the scales. For example the catchment scale climate influence on the tributary inflows and their impact on the groundwater levels conditioned on the farm scale climate which is linked back to the catchment scaled by the inclusion of end of system flows in the analysis.

The inclusion of an 'unknown' characteristic in the WOS WB tool provides an overview of the status of data collection for a particular valley. This is an important outcome in terms of prioritising the collection of data into the future.

The ability to bring elements that indirectly influence the water balance (eg. wheat yields) into the analyses provides considerable scope for developing Bayesian Networks that reflect individuals understanding of their own farm and how it fits in the catchment.

# 5 Recommendations for further work

This project has provided the foundations for further work in the area of assessing water use efficiency at a whole-of-system scale using a Bayesian Network technique. The farm scale Bayesian Networks developed for this project do not necessarily reflect actual practices in the valleys. Future work should focus on collating this farm scale information and incorporating it along with results from the irrigator behaviour review into the farm scale Bayesian Networks.

Stakeholders in each of the valleys have had very limited exposure to the Bayesian Networks and water balances developed for this project. Further work is required to test their reaction to the frameworks and capture their input through qualitative nodes in the Bayesian Networks.

Including modelled and actual data at the farm scale would add considerable value to the WOS WB tool, particularly with respect to the behaviour of groundwater as a function of particular farming systems. The WATERTRACK software, which calculates a daily water balance using data collected at the farm level, is an example of data that could be integrated into the WOS WB tool. The WATERTRACK software wasn't sufficiently developed at the time this report was completed, however including data from it will provide a more rigorous assessment between the links of the water balance at the different scales.

As part of this project a literature and survey review was conducted on the factors that influence crop planting and watering behaviour. Due to time and data constraints, the results of this review have not been incorporated into any of the Bayesian Networks developed, but there inclusion is an area for future work.

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**Attachment 2 to Determining whole-of-system Water Use Efficiency (DAN 14) Final Report for the National Program for Sustainable Irrigation (Land and Water, Australia)**

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NSW DEPARTMENT OF PRIMARY INDUSTRIES

# Determining Whole-of-System Water Use Efficiency for Macquarie and Murrumbidgee River Valleys

Final Milestone Report

for the

## National Program for Sustainable Irrigation (Land and Water, Australia)




Rueben Mubiru and Helen Fairweather
13th December 2004

# Acknowledgements

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Many thanks are due to the staff of HR Wallingford and Cranfield University who developed the computer model WaSim (Water Simulation) that was run to simulate water balance data and the developers of the CropWat model (FAO). Both of these models are available freely and provide valuable tools for the construction of water balance data of irrigation systems.

Many other people have contributed in one way or another. Our gratitude is extended to Garry Giddings (Irrigation Officer, NSW DPI), Col Mullen (District Agronomist, NSWAG), Barry Swann (Irrigation Advisory Officer, NSW DPI) for their "expert opinions and best guesses" relating to input data for different crop and soil parameters utilised in the simulation modelling undertaken for this project. The efforts of the pervious research officers (David Mitchell and Alan Emerson) and project supervisor (Nick Austin) are also gratefully acknowledged.

**Rueben's personal acknowledgement:** As the saying goes, behind every successful man there is a woman. I would like to thank the woman behind me, my wife Miki Ono for her support, encouragement and making me a very happy man.

# Summary

This project presents a methodology for determining Whole-of-System Water Use Efficiency. Initially the methodology was based on water balance frameworks that were developed at three nested and linked spatial scales (i.e. catchment, scheme and farm) and incorporated into a Bayesian Network, using the Netica software. It was thought that this approach of nesting the scales would identify the linkages or volume of water that flows between them and provide a valid assessment of the potential water savings that could be made at each scale. These water balances were applied to parts of the Macquarie and Murrumbidgee valleys. However, this approach required that all the elements of the water balance be dimensionally equivalent and available at the relevant temporal scales.

After reviewing the nested and linked spatial scales approach it became apparent that the power and flexibility provided by the Bayesian Network allowed a diversion from the application of the typical water balance and this revised methodology was applied to part of the Macquarie valley to assess irrigation efficiency at a Whole-of-System scale. Time did not permit the application of this second methodology to the Murrumbidgee dataset.

In both approaches data collection and computer simulation modelling were undertaken to quantify the elements of the water balance. The collected and modelled water balance data were determined by assessing the various incoming and outgoing water fluxes over the year at each scale. Data were collected from many sources that include state agencies (DIPNR, NSW DPI), electronic sources, industry experts, irrigation scheme records, the Integrated Quantity and Quality Model (IQQM) output (DIPNR), SILO and from other relevant research and industry reports.

The water balance framework that assess irrigation efficiency at a Whole-of-System scale, when applied to the Macquarie valley, indicated that at the defined Whole-of-System scale, irrigation efficiencies are more often in the higher range (~50 % probability of being >80%). However, recent measurements in the Macquarie valley have shown that at the field scale, irrigation efficiencies for furrow irrigated cotton are typically a lot less than 70%. These results indicate that the losses at the farm scale may becoming gains at the Whole-of-System scale.

The socio-economic and climatic factors influencing crop planting and watering behaviour and those required for successful Whole-of-System Water Use Efficiency assessment were also explored and their relevance to the present research highlighted. It has been found that the influences of these factors, unless managed well, can negatively impact on irrigated agriculture, communities and hinder economic development. It is however, acknowledged that irrigated agriculture in Australia is nested in a cultural context as well as a socio-economic one. The cultural “influences” can be very local and can help determine what is regarded as good farming practices in the area. No research work on the cultural influences and/or factors was undertaken. These were considered to be beyond the scope of the work undertaken for this project. Though these factors were not explicitly incorporated into the Bayesian Network methodology this research has indicated the potential for their inclusion.

It is not guaranteed that this report has identified all factors, information and data needed for successful Whole-of-System Water Use Efficiency assessment in the Macquarie and Murrumbidgee river valleys. However, in the opinion of the authors, the report provides a framework for taking the ideas forward.

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# 1 Introduction

Water is a scarce resource in Australia. This and other factors have led irrigated agriculture and the environment to increasingly compete for water. Competition for water has led to a call for improved farming practices and irrigation management that will in turn improve the effectiveness and efficiency of water use.

Today, methods that are thought to improve Water Use Efficiency, such as water harvesting, recycling of excess water and soil water monitoring have become increasingly popular and their usage show continued expansion in the process of food and fibre production, especially in areas with water scarcity and salinity problems.

Mitchell (2002) stated that these methodologies (i.e. water harvesting, recycling of excess water and soil water monitoring) and the determination of the water balance at a single scale look at system losses in isolation to identify water savings. This may create misleading perceptions about the volumes of water that could be saved and the overall system efficiency because water lost at one scale may be gained at another scale. For example, a farm scale water balance will correctly represent any deep drainage as a loss but cannot represent how these losses may become gains at the catchment scale (e.g. groundwater recharge). Lack of data further hampers any attempt to firstly define the water balance at any spatial or temporal scale.

There is also confusion surrounding the terminology "Water Use Efficiency" and the numerous ways it is determined. In some cases, Water Use Efficiency is used to express the effectiveness of irrigation water delivery and use. In other cases it describes a relationship between water delivered (input) and agricultural production (output). When used in this way, the term is in fact referring to an index of water use, not an efficiency (Barrett Purcell and Associates 1999).

This report aims to describe a methodology to determine Whole-of-System Water Use Efficiency for selected river valleys in NSW. The project has followed a stepwise process in firstly designing the conceptual water balance frameworks to describe Water Use Efficiency at the various scales. The second and third steps in the process are the collection of data required to assess Water Use Efficiency and the development of a tool to manipulate and analyse data. Bayesian Networks have been chosen to move the water balance framework from the conceptual stage to a tool for assessing Water Use Efficiency.

A methodology developed earlier in the project was applied to the Macquarie and Murrumbidgee valleys and a second methodology only to the Macquarie valley.

Both methodologies are based on water balance frameworks. The frameworks developed early in the project were developed at three nested and linked spatial scales (i.e. catchment, scheme and farm). Nesting the scales identifies the linkages or volume of water that flows between the spatial scales. This approach can be used to assess unaccounted for water at the various scales and therefore provides a valid assessment of potential water savings.

The methodology developed later in the project was focused only on the Whole-of-System scale and provides an assessment of irrigation efficiency at this scale.

Understanding the stochastic nature of the long-term water balances, coupled with the uncertainties makes the seemingly simple task of constructing a water balance, very complex. In an attempt to handle this complexity a Bayesian Network technique was used to construct the water balances in this project. In essence, Bayesian Networks provide a method to represent relationships between variables even if relationships involve uncertainty, unpredictability or imprecision. Links between variables can be established deterministically or probabilistically by observation or expert opinion.

For the purpose of this project, the Bayesian Networks have been developed and used as an analyses tool in an attempt to handle the complex, uncertain and stochastic nature of water balances over time. Bayesian Networks can be used to support analysis of the consequences of possible decision choices by making information and data easily accessible and allowing "what if" analyses. The computer software "Netica" (Norsys 1998) was used to construct the Bayesian Networks in the form of a computerised database and interface. Netica provides a picture (graphical) based explanation of the Bayesian Network.

It is expected that the methodologies developed from these focus areas (Macquarie and Murrumbidgee valleys) will be transferable to other river valleys. In this report the term "catchment" is used interchangeably with "valley".

## *1.1 Project Direction*

The emphasis in this project has been on the development of a methodology to assess Whole-of-System Water Use Efficiency for two river valleys (Macquarie and Murrumbidgee). The project also aims to recommend the tools that can be used to assess where real water savings can be found by collating all available data sources and outlining a methodology to analyse these data in a water balance framework.

The developed Bayesian Networks provide the framework to represent relationships between variables even if relationships involve uncertainty, unpredictability or imprecision and to draw together quantitative (output from crop and catchment scale models, river diversions, groundwater levels, research data etc) and qualitative data (subjective assessments where quantitative data is unavailable) from all available sources. The framework is intended to provide a more rigorous methodology for determining where improvements in Water Use Efficiency can be made.

The following objectives were required to be met by this project:

- Improved understanding of Whole-of-System water balances within the Macquarie and Murrumbidgee valleys.
- Greater definition of irrigation delivery and application systems, and their interaction at farm, scheme and catchment levels.
- Assessment and prioritisation of opportunities for increased Water Use Efficiency.
- Quantification of potential water savings through increased farm, sub catchment and valley wide efficiency in the Macquarie and Murrumbidgee river valleys of NSW.
- Documentation of the factors influencing crop planting and watering behaviour and those that are required for successful Whole-of-System Water Use Efficiency assessment.

It is recognised that some of these objectives are met by providing the starting point for a methodology to assess Water Use Efficiency based on a water balance (particularly objectives 2 and 4).

This project did not include a validation phase and the developed tool is used to demonstrate a methodology for assessing unaccounted for water and Water Use Efficiency in a water balance framework.

## *1.2 Outline of the Report*

This report mainly deals with four aspects of assessing the irrigation water balance:

(1) The current knowledge on Water Use Efficiency,

(2) Data collection and simulations modelling techniques undertaken to quantify the water balance frameworks,

(3) Development of the Bayesian Networks as a tool to structure the water balance and support assessment of Whole-of-System Water Use Efficiency and unaccounted for water at various scales, and

(4) Documentation of the socio-economic and climatic factors influencing crop planting and watering behaviour.

Finally, several conclusions are drawn and areas for further future research are recommended.

# 2 Whole-of-System Water Use Efficiency

## 2.1 Water Use Efficiency Defined

There has been considerable confusion about the term Water Use Efficiency for many years. Water Use Efficiency has been defined in many different ways for different components of irrigation and dryland farming systems. In some cases, Water Use Efficiency is used to express the effectiveness of irrigation water delivery and use. In other cases, it has been used to describe a relationship between water delivered or available (input) and agricultural production (output). When used in this way, the term is in fact referring to an index of water use, not an efficiency of water use (Barrett Purcell and Associates 1999).

In an attempt to reduce this terminology confusion, Barrett Purcell and Associates (1999) asserted that "efficiency" is a dimensionless term that is obtained by dividing values with equivalent units. Barrett Purcell and Associates (1999) also suggested that Water Use Efficiency should be used as an umbrella term or as a generic label for a toolbox with two compartments. Compartment one is a framework for efficiency measures based on the calculation of a water balance (dimensionless), and the second compartment contains a suite of performance indices e.g. tonnes per megalitre or gross margins per megalitre. The term Water Use Efficiency should be restricted to a generic label for any performance indicators used to study water use in crop production. This label, Water Use Efficiency, need not be defined but should be considered like a label on a toolbox. Inside the toolbox are many specific performance indicators that should be referred to as water use indices. Any water use index (within this tool box) should be clearly defined with specific units when used. This concept has been adopted throughout project. Any water use index is clearly defined with the specific units used.

## 2.2 Whole-of-System Water Use Efficiency

Improving Water Use Efficiency involves increasing output per unit of water, reducing losses to sinks, reallocating water to higher priority uses and reducing water degradation (Howell 2001). The major requirement to achieving improvements in these areas is to quantify and qualify the water balance and measure the losses at the scale of interest, as well as the Whole-of-System scale. Assessing the quantity and quality of these losses provides information to assess the efficiency and effectiveness of irrigation at a range of scales.

According to Mitchell (2002) the available methods that use water in a more efficient way (i.e. water harvesting, recycling of excess water and soil water monitoring) and the determination of the water balance at a single scale look at system losses in isolation to identify water savings. This may create misleading perceptions about the volumes of water that could be saved and the overall system efficiency because water lost at one scale may be gained at another scale. For example, water losses at the farm scale (e.g. deep drainage) may become a gain at the catchment scale (e.g. groundwater recharge).

The Whole-of-System perspective is required if a valid assessment of the potential water savings is to be obtained. When a multiple scale approach is used unaccounted water can be identified. Measuring Whole-of-System Water Use Efficiency is conceptually and logistically complicated, certainly more complicated than measuring efficiency in any one of the sub systems, since losses at one scale may not necessarily be a loss in the whole system. Some of the water that is lost at one scale may become a gain at another scale. However the rate of return of these lost flows can vary in time. For example, deep drainage may occur over a few hours, yet it may be many years before the water returns through the groundwater system and is measured as streamflow.

The work in this report was initiated as a study to model a Whole-of-System water balance and the Bayesian Networks have been employed to help model the complex interactions between different components of the water balance at various scales. Efficiency indices to assess the overall performances in relation to crop water use are calculated.

Appendix A describes the major efficiencies and indices considered for this project.

# 3 Water Balance

A mass balance, which simply states that the sum of the inputs must equal the sum of the outputs plus any change of state, can provide information on the behaviour of a system. A water balance is a particular application of mass balance principals, which have been applied extensively in agricultural systems modelling. For example, many irrigation models that simulate the dynamics of soil moisture use a water balance methodology.

Quantifying the components of a water balance of a defined area provides an indication on the behaviour of the system. However, there is a great deal of uncertainty associated with each of the components of the water balance, particularly as the scale increases. For example at the field scale, measurements can be taken across the field to describe the heterogeneity of the field and therefore quantify, at least partly, the variability and uncertainty associated with the measurements. However at the catchment scale it is not physically possible to take sufficient measurements to quantify this uncertainty, though the variability may be represented.

When attempting to use a water balance to characterise a system, a method that incorporates the uncertainty of the variables may provide insights into our understanding of a system. Bayesian Networks are a tool that can be used to characterise this uncertainty, yet still allow some confidence that it provides reasonable representation of the system characteristics.

## *3.1 Traditional water balance*

The traditional water balance approach is to determine the variables that make up the inputs and outputs and then construct a simple mathematical equation (Equation 1) to represent this water balance. This approach requires that all the variables in the equation are dimensionally equivalent, can be identified as an input or an output and are able to be quantified with some certainty. However, this is rarely the case when examining the water balance of farms, irrigation regions and catchments.

$$P + SWin + CR = SWout + DD + ET + \Delta S$$ ........................................................ **Equation 1**

where
P is precipitation;
$SW_{in}$ is surface water flowing in to the system;
CR is capillary rise;
$SW_{out}$ is surface water flowing out of the system;
DD is deep drainage;
ET is evapotranspiration; and,
$\Delta S$ is the change in storage.

The application of this simple water balance equation is complicated by the uncertainty surrounding the input data and in some case the non-existence of the required data. Where quantitative data is missing, the Bayesian Network will still provide an answer if qualitative data is used.

At a catchment scale, the variables that contribute to the water balance are the inputs into the catchments (rainfall, dam releases and groundwater contributions) and the outputs (evaporation, diversions, groundwater contributions and end of system flows). Groundwater appears as both an input and an output as the direction of flow depends on the hydraulic gradient.

# 4 Water Balance Frameworks

## *4.1 Water Balance Boundaries*

Irrigation is the practice of diverting water from its natural flow path in a catchment to apply to a field and hence operates over many different spatial and temporal scales (Bos *et al.* 1994). A traditional water balance can be constructed and quantified over any scale provided the boundaries are properly identified. Appendix B describes the spatial and temporal boundaries that were established for the initial water balances that were constructed at catchment, scheme and farm scale for the Macquarie and Murrumbidgee river valleys. Brief descriptions of the Macquarie and Murrumbidgee catchments and their respective irrigation schemes are also included.

A stepwise process was followed to develop a framework for assessing Whole-of-System Water Use Efficiency for this project. The first framework developed was based on water balances at three nested and linked spatial scales (i.e. catchment, scheme and farm). The water balance frameworks at each scale were developed by assessing the incoming and outgoing water flux at each scale during the time period of interest. Elements that were considered in constructing the water balances included accounted for water (volume or flow rate is wholly accounted for in the water balance), partially accounted for water (volume or flow rate information is partially known) and unaccounted for water (volumes or flow rates are unknown).

Even though the accounted for water can be either measured or predicted with reasonable accuracy there are error bands that should be quantified and these error bands increase considerably with the partially accounted for and unaccounted for water. This uncertainty is an important part of characterising a water balance. The traditional water balances (equations) constructed for the initial methodology developed for this project are included in Appendix B.

# 5 Methodology 1: A framework based on a dimensionally equivalent water balance

## *5.1 Bayesian Networks*

The uncertainty associated with assessing Water Use Efficiency comes from the heterogeneity of the variables of interest at both temporal and spatial scales. Increasing the quantity of reliable data decreases the uncertainty of the Water Use Efficiency measure at both the temporal and spatial scales.

Due to the nature of the factors that influence Water Use Efficiency (climate, soils, knowledge and skills, decision making etc) there is also spatial and temporal variability associated with this measure. Characterising this variability is important when making an assessment of Water Use Efficiency at any scale.

Bayesian Networks provide the tool to characterise and deal with both the uncertainty and variability associated with the parameters that influence a measure of Water Use Efficiency. The variability of the parameters used to assess Water Use Efficiency is characterised by assigning the range of states that are possible for each particular variable. The uncertainty of the parameters (and their states) is characterised by assessing the probability relationships between the parameters in the many combinations of states that are possible.

## *5.2 Linkages Between Scales*

Once the water balance components were identified at each spatial scale, the linkages, or volumes of water that flow between the spatial scales became more evident. These linkages (Figure 1) between spatial scales may include irrigation water diversions from a catchment scale to a scheme or recharge to a regional aquifer that in turn may be pumped for irrigation at farm scale.

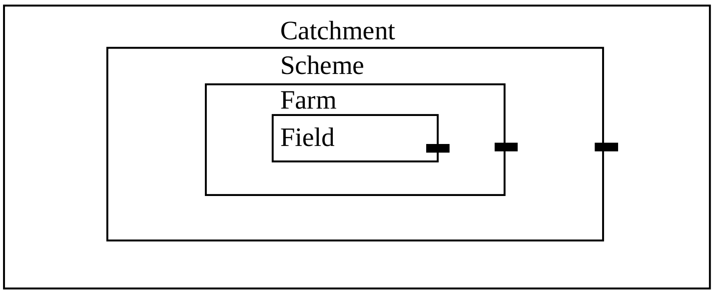


**Figure 1. Conceptual diagrams representing the irrigation cycle (linkages between scales are represented by the thick black lines).**

The linked scales were utilised in the first methodology established for assessing Water Use Efficiency (or unaccounted for water) (Figure 2), but limited time prevented them from being applied to the second methodology. However, incorporating these linkages into the redesigned water balance framework will provide a more complete picture of Water Use Efficiency from the catchment through to the farm and field scales. See Appendix B for more information relating to the development of these linkages and a full description of the nodes.

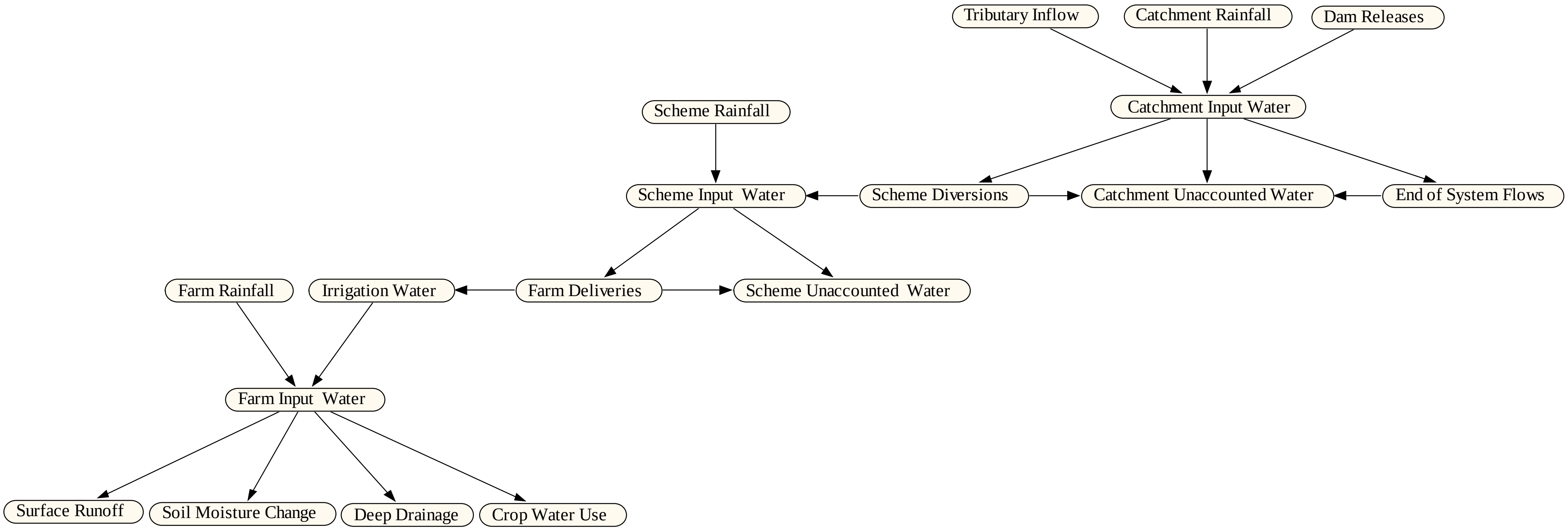


**Figure 2. Master Bayesian network representing Whole-of-System water balance variables (nodes) for NSW River Valleys.**

## *5.3 Data Collation*

Various tools are currently used to collate and analyse the water balance data. These tools include Excel, Access, Netica (Bayesian Network software) and various daily time step crop water use models (WaterMod and Wasim).

Input into Bayesian Networks are in the form of a probability distribution. These distributions can be determined from time series data, output from models or from best guesses of quantitative and qualitative data (Figure 3).

Appendix C describes the considerable data collection that was undertaken for the compilation of the initial methodology developed for assessing Whole-of-System Water Use Efficiency. These data were collected for the Macquarie and the Murrumbidgee valleys. Most of the data collected for the Macquarie valley were utilised in the development of the second methodology.

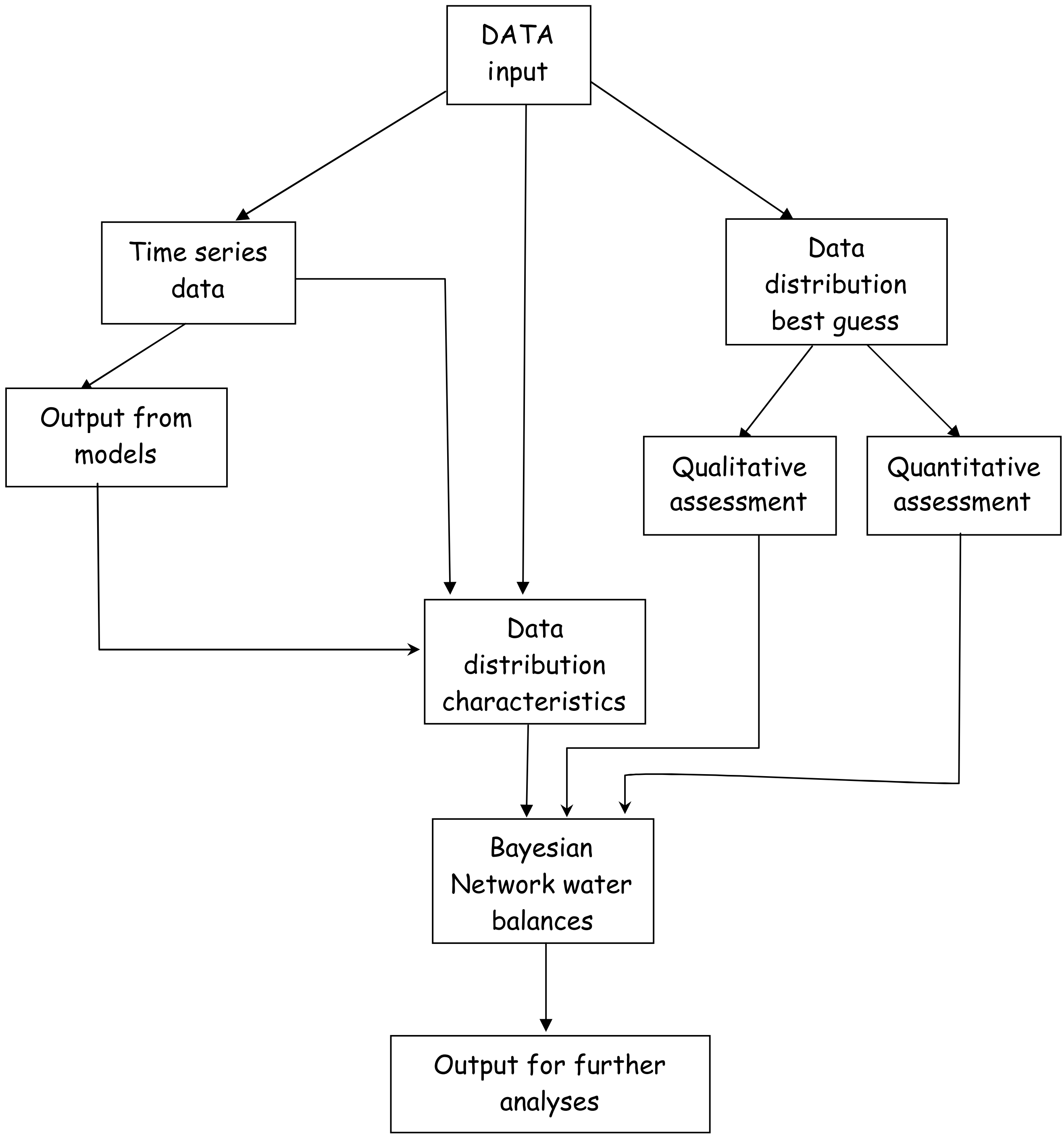


**Figure 3. Data flow diagram**

## *5.4 Results of the Bayesian Networks Structure*

The Bayesian Networks developed in the first instance were utilised to investigate:

(1) the influence of key management interventions on project objectives, and

(2) the sensitivity of the project objectives (i.e. water use efficiencies, unaccounted for water, etc) to management interventions.

The links between the water balance and other variables were identified based on a cause to effect assessment and the Bayesian Network set to particular states.

Several analyses were conducted on the master Bayesian Network (Figure 2) by incorporating files that contained data on water in the Macquarie and Murrumbidgee valleys. A factor of 100 has been used to convert all water balance values for catchment scales, for example, 3 – 6 GL means 300 – 600 Gigalitres at the catchment scale.

### 5.4.1 Unaccounted for water

Figure 4 shows the master Bayesian network in expanded form that has been compiled after incorporating files that contained water balance data for the Narromine scheme only. Figure 5 shows the comparison of the probability that unaccounted for water will be in a certain range when water is diverted form the Macquarie river system to various irrigation schemes (Narromine, Tenandra, Buddah Lakes and Grenhide) for irrigated cotton. The unaccounted for water is over the period of 6 years (1995 – 2000).

The Bayesian network results show that the probabilities for particular ranges of unaccounted for water at the scheme scale have some variations between them but broadly agree with each other. The greatest variation in the chance that high volume of water will be lost at scheme scale is for the Narromine irrigation scheme with a probability of 41.6% that unaccounted for water will be between 6 – 9 GL, given all the interactions represented in Figure 4.

When water is diverted to Narromine irrigation scheme, there is a 25.1% chance that unaccounted for water at the scheme scale (SUW) will be between 0 – 3 GL, a 33.3% chance that SUW will be between 3 – 6 GL and a 41.6% chance that SUW will be between 6 – 9 GL.

Similarly, for Tenandra irrigation scheme, it was found that there is a 29.2% SUW will be between 0 – 3 GL, a 40.8% chance that SUW will be between 3 – 6 GL and a 30% chance that SUW will be between 6 – 9 GL.

Results for Buddah Lakes irrigation scheme indicated that there is a 49% chance that SUW will be between 0 – 3 GL, a 25.5% chance that SUW will be between 3 – 6 GL and a 25.5% chance that SUW will be between 6 – 9 GL.

When water is diverted from the river system to Greenhide irrigation scheme, there is a 51.4% chance that SUW will be between 0 – 3 GL, a 24.3% chance that SUW will be between 3 – 6 GL and a 24.3% chance that SUW will be between 6 – 9 GL.

The Narromine irrigation scheme is the largest scheme in the Macquarie valley with a total length of approximately 350 km of delivery channels and a total area of 120,000ha (Elliot 1995). Since the volume of unaccounted for water at the scheme scale is attributed to evaporation, seepage losses and measurement errors in the delivery system the results are expected. Even a slight change in the dimensions and condition of the delivery channels can affect the rate of seepage losses considerably.

Mitchell (2002) stated that the deep drainage from the channels may flow to an alluvial aquifer located 50m-110m deep. There are links between the Macquarie River and an alluvial aquifer that underlies the Macquarie Valley (Keshwan and O'Shaughnessy 1999) but the volume of water that flows into that aquifer has not been quantified for this study. Water from this aquifer is pumped by irrigators in the Narromine irrigation system. Research conducted on the area show that the groundwater behaviour of the alluvial aquifer does not show a clear recharge component coincident with rainfall (Keshwan and O'Shaughnessy 1999). There does not appear to be a strong link between the shallow watertable and the alluvial aquifer. Seepage losses from the channels may have contributed to the development of a shallow watertable in the Narromine irrigation scheme. Currently the shallow watertable is between 10-30 m deep (Narromine Irrigation Board of Management 2001). Water may be recaptured from this shallow aquifer provided the water in the shallow aquifers is not too saline.

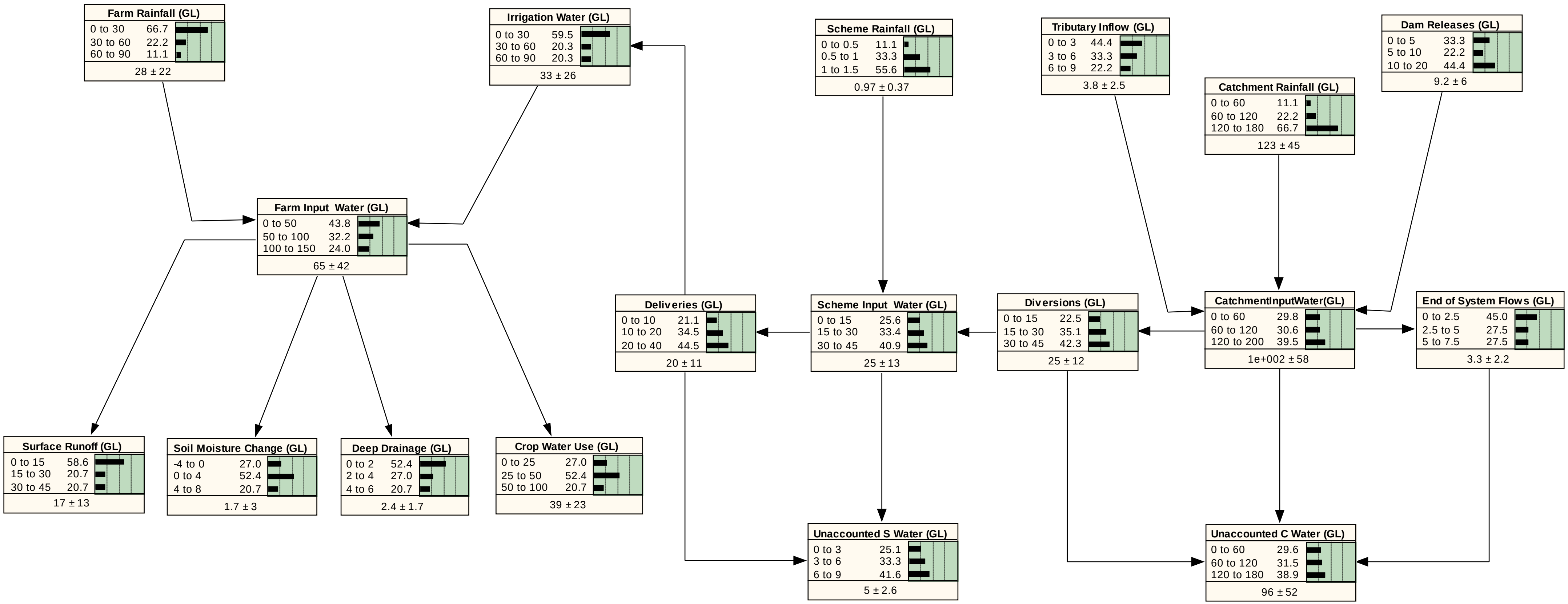


**Figure 4. Macquarie valley Bayesian network showing Whole-of-System water balance probability distribution**

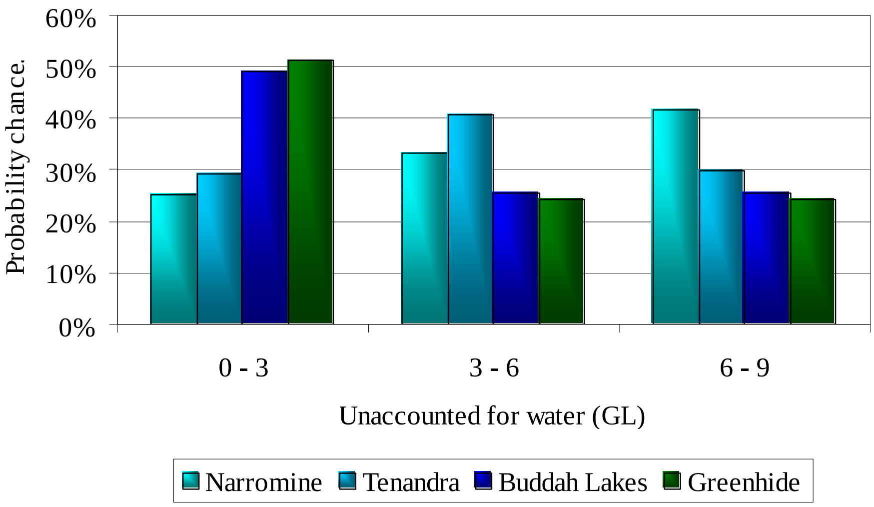


**Figure 5. Unaccounted for water Bayesian Network belief probabilities**

### 5.4.2 Conveyance Efficiency

Figure 6 shows the scheme scale Bayesian Network representing the impact of the volume of water inputs and volume of water delivered to the farms on conveyance efficiency for the Narromine irrigation scheme. Conveyance efficiency is the efficiency of the scheme system to deliver water to the farm. i.e., the ratio between the water delivered to the farm gate against the amount of water diverted from the Macquarie River to the Narromine scheme.

Table 1 presents the results for the Tenandra, Buddah Lakes and Greenhide irrigation schemes.

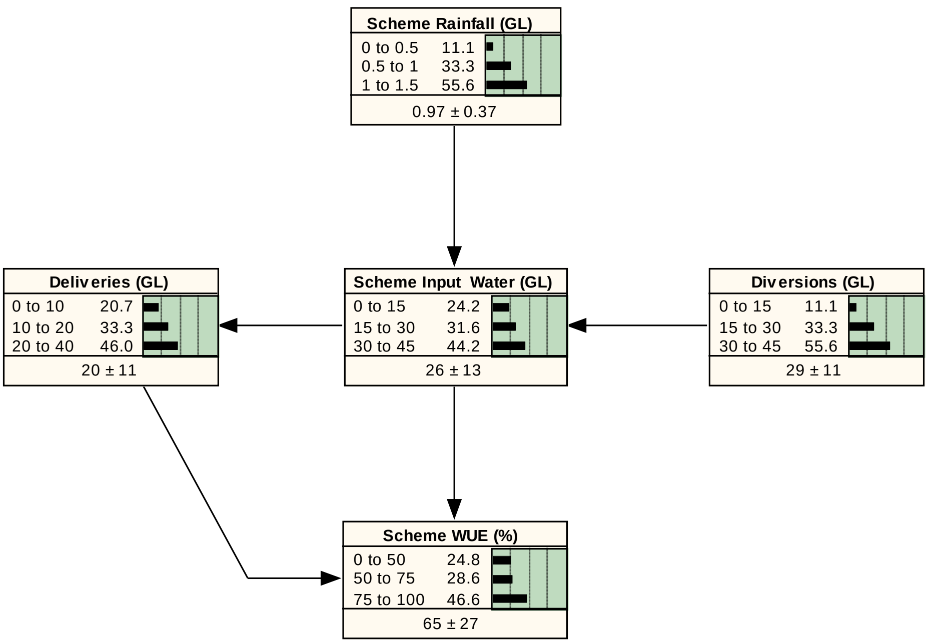


**Figure 6. Scheme scale Bayesian network diagram for assessment of scheme Water Use Efficiency**

**Table 1. Conditional probabilities for the scheme Water Use Efficiency**

| **Scheme Water Use Efficiency** | **0 – 50%** | **50% – 75%** | **75% – 100%** |
|---|---|---|---|
| Buddah Lakes | 24.8% | 24.8% | 50.4% |
| Tenandra | 25.8% | 25.8% | 48.5% |
| Greenhide | 22.9% | 22.9% | 54.1% |

The best result is produced when water is delivered to the farms via Greenhide irrigation scheme where there is a 22.9% chance that scheme water conveyance efficiency (Scheme Water Use Efficiency) will be between 0 – 50%, a 22.9% chance that scheme Water Use Efficiency will be between 50% – 75 % and a 54.1% chance that scheme Water Use Efficiency will be between 75% – 100%. This result reinforces the fact that Greenhide irrigation scheme is a relatively small scheme with only 30 km of delivery channels (Hope 2003) and covers a much smaller area compared to other schemes.

Appendix E provides some more examples of the use of Bayesian Network for assessing unaccounted for water and Water Use Efficiency at the farm scale for the Macquarie and Murrumbidgee valleys. At the farm scales the Bayesian Networks shown in Appendix E are for the purpose of demonstrating the methodology and do not necessarily reflect the actual conditions in either valley.

# 6 Methodology 2: A multi-dimensional water balance framework developed using Bayesian Network

Similarly to the traditional water balance approach the second methodology developed requires that all the variables that impact on the water balance are identified, however they do not have to be dimensionally equivalent, do not have to be explicitly identified as an input or output and their state (or potential states) can be quantified or qualified as a distribution of values rather than a single value.

The Bayesian Network also allows the incorporation of variables that may impact on the water balance but may not be explicitly quantified (eg. reference evapotranspiration).

## *6.1 The water balance variables required to assess Water Use Efficiency at the catchment scale*

The water balance is a useful instrument for assessing Water Use Efficiency at the catchment scale as it provides a mechanism for identifying the variables that have direct impacts on the assessment. Implementing the water balance framework in a Bayesian Network then enables the inclusion of variables that indirectly influence the water balance and hence the assessment of Water Use Efficiency.

At the catchment scale the variables that can be directly quantified in the water balance are the inputs (rainfall across the catchment, dam releases, tributary inflows), outputs, (evapotranspiration (or crop water use) across the catchment, end of system flows, irrigation and town water diversions) and groundwater, which can be both an input and an output.

There are other variables that will also impact on the water balance but may not be quantified in the application of the typical mathematical representation of the balance: water allocations, effective rainfall and irrigation requirements. The construction of a Bayesian Network will provide a mechanism for incorporating variables of this type that are not easily incorporated into the traditional water balance equation.

## *6.2 Data collection in the Macquarie Valley*

### 6.2.1 Temporal Scale

Several factors need to be considered when deciding the time scale that is most appropriate for the assessment of Water Use Efficiency at the catchment scale:

- The availability of data at various time steps,
- The frequency of measurement of the variable of interest, and
- The reporting period of variables (if relevant).

Climatic data (rainfall, temperature and evaporation) are available at daily time steps (hourly in some cases), but can readily be aggregated to monthly or annual time steps. Crop water use and irrigation requirement can be calculated directly from these climatic data when combined with farm information (crop type, planting date, stages of growth and soil type). Therefore crop water use and irrigation requirement can also be calculated at daily time steps and aggregated to monthly or annual time steps.

Burrendong Dam releases, flows at the defined end of system (Corinda in the Macquarie River), gauged tributary inflows, water allocations, irrigation and town water supply diversions are all readily available as annual totals. These annual totals are based on the July to June water year.

In the Macquarie Valley, groundwater levels at various locations have been collected since 1905. There are considerable discontinuities and irregularities with respect to sampling intervals in this dataset. The number of water levels taken at each bore range from 2 to 890. The sampling interval ranges from 1 day to several decades in some cases.

Given the availability of most of the required data at an annual time step, the groundwater dataset was investigated to determine the applicability of extracting an average change in water level from July to June in any given year. The number of records contributing to the annual groundwater change ranges from 2 to 57 with no data available in 6 years (Figure 7).

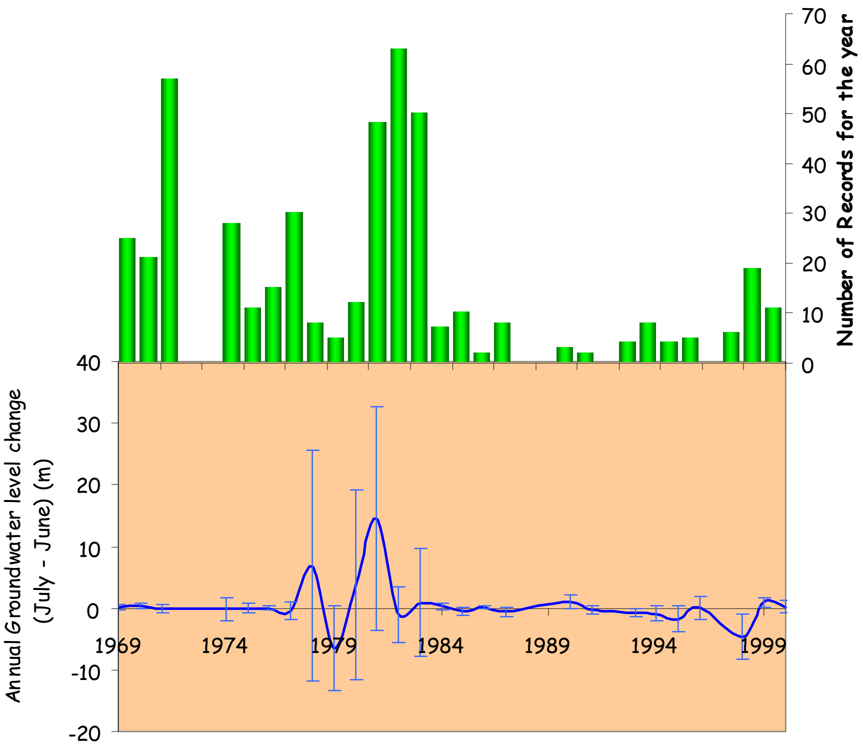


**Figure 7. Annual Groundwater level changes in the Macquarie valley (July to June) from 1969 to 2000 (error bars +/- 1 standard deviation) and the number of records contributing to the calculation.**

The CropWat model (FAO 1998), which was used to calculate the annual crop water and irrigation requirements, requires inputs of crop planting dates, stages of growth and associated crop coefficients, soil information (total available moisture, maximum rain infiltration rate, maximum rooting depth and the initial soil moisture depletion), and climatic data.

Reference evapotranspiration is a required input into the CropWat model (FAO 1998) and this can be entered directly or calculated from the monthly data (maximum and minimum temperatures, humidity, wind speed and sunshine hours). A time series of monthly averages was required for the years from 1967 to 2000 and wind speed data are not available over this time.

Reference evapotranspiration can also be calculated from pan evaporation data if there are reliable pan coefficients available. Pan coefficients were collected as part of the volumetric conversion process several years ago (Austin *et al.* 2002) and used with the historical pan evaporation data to convert area based licences to volumetric licences based on modelled crop water use. The pan coefficients for each month of the year for Narromine were used with the average daily pan evaporation (Dubbo, Trangie and Warren from the SILO patched point dataset) to calculate the average daily reference evapotranspiration for each month from 1967 to 2000.

Crop data (planting dates, stages of growth, root depths and crop coefficients) were also obtained by survey for the volumetric conversion process and for the development of the Macquarie valley profile (Austin *et al.* 2002, Hope 2002). Percentage of areas planted to different crops was also obtained from the data collected for the profiles (unpubl.) from 1989 to 2000. CropWat (FAO 1998) allows the input of the percentage areas to calculate the water use for up to 30 crops grown at the one time.

Monthly rainfall totals and an effective rainfall percentage are also required inputs into the CropWat model (FAO 1998). The effective rainfall percentage was aggregated from the monthly effective rainfall percentages from the modelling that was carried out for the volumetric conversion study for a range of crops for each month for the Central West zone (Austin *et al.* 2002).

## *6.3 Compiling the time series*

The Burrendong dam releases (IQQM modelled data), gauged tributary inflows, irrigation and town water diversions and the flows at the defined end of system (Carinda) were obtained from the State Water database (D Barnes pers comm) and annual reports (McCormick and Bell 2000; Gardner and West 1999).

Daily rainfall since 1967 for three stations from the top, middle and bottom of the study area (Dubbo, Trangie and Warren) were obtained from the SILO patched point dataset. These were aggregated to annual values (July to June) and the average of the three values used as input to the catchment scale water balance framework (Figure 8).

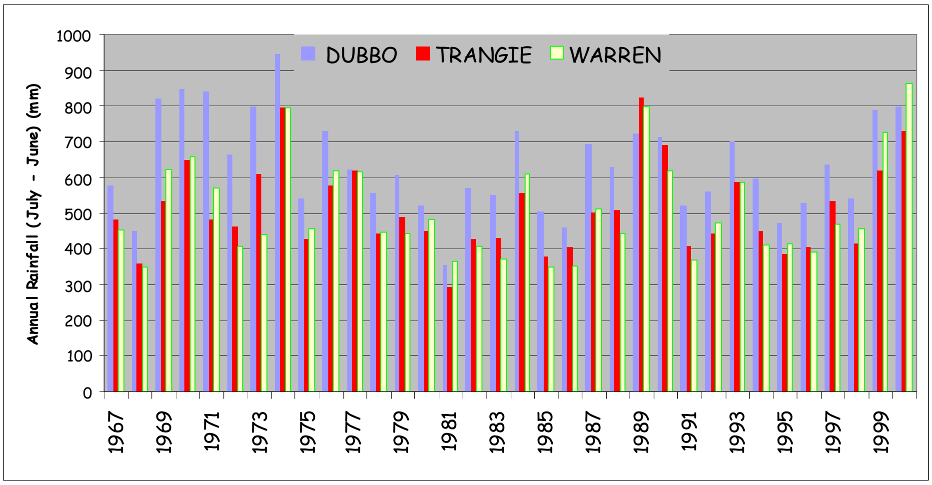

**Figure 8. Annual rainfall totals (July to June) for Dubbo, Trangie and Warren in the Macquarie Valley from 1967 to 2000.**

## *6.4 Modelling crop water use, irrigation requirement and effective rainfall*

### 6.4.1 Configuring the inputs into CropWat

Monthly rainfall totals from 1967 to 2000 and the effective rainfall percentage (73%) were also aggregated (average of the Dubbo, Trangie and Warren data) and configured for input into the CropWat model (FAO 1998). Reference evaporation daily averages for each month from 1967 to 2000 were also compiled. This resulted in a total of 68 climate input files for the CropWat modelling.

The same crop classes used in the volumetric conversion process (Austin *et al.* 2002) were used as input into the CropWat model (FAO 1998) and the percentage area grown for each year estimated from the data collected for the profile (unpubl.). Table 2 shows the averages of these data.

**Table 2. Average percentage area grown for each crop class in the Macquarie valley.**

| Crop Class | Average percentage area grown |
|---|---|
| Annual Pasture | 4% |
| Citrus | 1% |
| Cotton | 62% |
| Lucerne | 7% |
| Orchards | 1% |
| Perennial Pasture | 1% |
| Pulses | 1% |
| Summer Oilseeds | 5% |
| Summer Cereals | 5% |
| Vegetables | 1% |
| Vines | 1% |
| Winter Cereals | 10% |
| Winter Oilseeds | 1% |

When there was more than one crop identified for each class an average was used for the crop data (planting dates, initial and final rooting depths, stages of growth and crop coefficients (kc)). The CropWat model (FAO 1998) also requires as input, factors during the growing season that are used to calculate the yield response to soil moisture (ky) and the average fraction of total available soil water that can be depleted from the root zone before moisture stress occurs [0-1] (p) (

Table 3).

A total of 11 crop information files were configured for input to CropWat along with 34 cropping pattern files that contained information on the percentage of area for each crop planted for each year from 1967 to 2000.

The configuration of all the CropWat input files was automated in Excel© with the use of the VBA programming language.

**Table 3. Crop data required as input for CropWat (FAO 1998)**

| | | From Volumetric Conversion Survey (Austin et al. 2002) | | | | | | | | | From CropWat database | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Crop Coefficients | | | Growth Stages - Number of Days | | | | Rooting Depth (m) | | Yield response to soil moisture factor | | | | | Average fraction of soil water that can be depleted from the root zone before moisture stress occurs [0-1] | | |
| Crop Class | Planting Date | kc1 | kc3 | kc4 | 1 | 2 | 3 | 4 | Initial | Final | ky1 | ky2 | ky3 | ky4 | ky5 | p1 | p3 | p4 |
| Annual Pasture | 1-Mar | 0.4 | 0.95 | 0.4 | 50 | 70 | 100 | 55 | 0.2 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 |
| Citrus | 1-Apr | 0.7 | 0.65 | 0.7 | 150 | 90 | 90 | 35 | 0.2 | 1.4 | 1 | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0.5 |
| Cotton | 1-Oct | 0.35 | 1.2 | 0.6 | 30 | 50 | 70 | 35 | 0.2 | 1.5 | 0.4 | 0.4 | 0.5 | 0.4 | 0.85 | 0.6 | 0.6 | 0.9 |
| Lucerne | 1-Sep | 0.4 | 0.95 | 0.9 | 10 | 30 | 150 | 35 | 0.2 | 0.8 | 1 | 1 | 1 | 1 | 1 | 0.55 | 0.55 | 0.55 |
| Orchards | 1-Sep | 0.55 | 0.9 | 0.65 | 15 | 75 | 90 | 60 | 0.2 | 0.6 | 1 | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0.5 |
| Perennial Pasture | 1-May | 0.4 | 0.9 | 0.8 | 120 | 62 | 120 | 63 | 0.2 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 |
| Pulses | 1-May | 0.4 | 1.05 | 0.85 | 120 | 62 | 120 | 63 | 0.2 | 0.8 | 0.4 | 0.6 | 0.8 | 0.6 | 0.8 | 0.6 | 0.6 | 0.8 |
| Summer Oilseeds | 1-May | 0.5 | 1.15 | 0.3 | 90 | 45 | 40 | 60 | 0.2 | 0.75 | 0.4 | 0.8 | 1 | 0.4 | 0.85 | 0.5 | 0.6 | 0.9 |
| Summer Cereals | 23-Nov | 0.4 | 1.15 | 0.5 | 10 | 40 | 82 | 15 | 0.2 | 1 | 0.4 | 0.4 | 1.3 | 0.5 | 1.25 | 0.5 | 0.5 | 0.8 |
| Vegetables | 1-Aug | 0.5 | 1.15 | 0.75 | 25 | 30 | 45 | 30 | 0.2 | 0.4 | 0.45 | 0.8 | 0.8 | 0.3 | 1.1 | 0.25 | 0.3 | 0.5 |
| Vines | 1-Aug | 0.4 | 0.7 | 0.4 | 20 | 40 | 120 | 60 | 0.2 | 1.5 | 0.2 | 0.7 | 0.85 | 0.4 | 0.85 | 0.4 | 0.4 | 0.4 |
| Winter Cereals | 1-May | 0.3 | 1.15 | 0.25 | 20 | 40 | 75 | 45 | 0.2 | 1.4 | 0.2 | 0.6 | 0.5 | 0.4 | 0.6 | 0.6 | 0.6 | 0.9 |
| Winter Oilseeds | 1-May | 0.35 | 1.15 | 0.35 | 25 | 40 | 65 | 50 | 0.2 | 0.75 | 0.4 | 0.6 | 0.8 | 0.8 | 0.95 | 0.45 | 0.5 | 0.8 |

## *6.5 CropWat modelling*

As the soil information required by CropWat is limited to the total available moisture, the maximum rain infiltration rate, the maximum rooting depth and the initial soil moisture depletion, a generic medium type soil was selected with 140mm/m depth, 40mm/day, 9m and 0% values used for each parameter, respectively. Testing of CropWat output showed very little sensitivity to this parameter.

Configuration files were constructed for each year from 1967 to 2000 and these files were manually input to CropWat and a report generated that split the predicted crop water use, irrigation requirement into totals for the first half (Jan to Jun) and second half of the year (Jul – Dec). Also included in this output was the total percentage of area planted to any crop over that time. The report was split in this way so that annual totals could be calculated to align with the water year (July to June) totals used for the rest of the water balance data.

### 6.5.1 Defining the boundaries

It was initially thought that all the inputs into the water balance would need to be dimensionally equivalent for the definition of the water balance (see appendix B). However as the power and flexibility provided by the Bayesian Networks became more apparent, there was evidence to suggest that dimensional equivalence was not a perquisite and therefore a mixture of depths, volumes and percentages could be used as input into the water balance framework. This approach did, however, pose some problems for defining the boundaries for the framework.

The Burrendong dam releases provide a natural upstream boundary and the Carinda stream gauging data defines a natural downstream boundary as an end of system flow. Other inputs into the system are rainfall, tributary inflows and groundwater base flows. However some of the rainfall becomes tributary inflow and groundwater base flow, some of the tributary inflows become groundwater base flow and visa versa. Separating these components is not a trivial task (if at all possible) and therefore makes the application of a typical water balance framework difficult (see appendices B to D).

Because rainfall, crop water use and irrigation requirement are entered into the water balance as a depth (mm) it is not necessary to define the lateral boundaries for the water balance. However to calculate an irrigation efficiency an area irrigated is required to convert the irrigation requirement depth to a volume.

### 6.5.2 Area irrigated

To calculate a volumetric efficiency an estimate of the area irrigated is required for each year the water balance is constructed. A limited annual time series (12 years) of irrigated area in the Macquarie Valley downstream of the Burrendong dam was obtained for the compilation of the profile data (unpubl.). The average of the 12 years was used in the years no data were available.

### 6.5.3 Irrigation efficiency

To evaluate the performance of a valley or study area requires some measure of the efficiency of the system. As described in the introductory section of this report an efficiency can be a ratio of two entities with equivalent dimensions, in which case it is referred to as an efficiency, or as a ratio of two entities that do not have equivalent dimensions, in which case it is referred to as an index.

A volumetric efficiency was calculated by converting the irrigation requirement in mm to a volume (GL) by using the unpublished area irrigated data. This efficiency was defined as the irrigation requirement (GL) divided by the sum of the water diverted for irrigation and the average change in groundwater level multiplied by the area irrigated (GL).

Because of the uncertainty associated with the values for the area irrigated, two other irrigation efficiencies/ratios were constructed to test the sensitivity of the measure; one using two volumetric measures and the other depth measures.

The additional volumetric efficiency is referred to as a project efficiency and is described by Equation 2.

$$PE = \frac{dv}{dr - tw - EOS} \qquad \text{......... Equation 2}$$

where
*dv* are the irrigation diversions,
*dr* are the releases from Burrendong dam,
*tw* are the town water diversions,
*EOS* are the end of system flows (measured at Carinda), and
*PE* is the project efficiency.
(all in GL)

The depth ‘efficiency’ is a ratio of the irrigation depth to the ground water change (both in mm). A comparison of the three efficiency measure histograms (both raw data and belief probabilities from the Bayesian Network), indicates that their distributions are very similar (Figure 9). Irrigation efficiency as a function of irrigation requirement, area irrigated, irrigation diversions and average change in ground water levels over the irrigated area was used in subsequent analyses of the Bayesian Network.

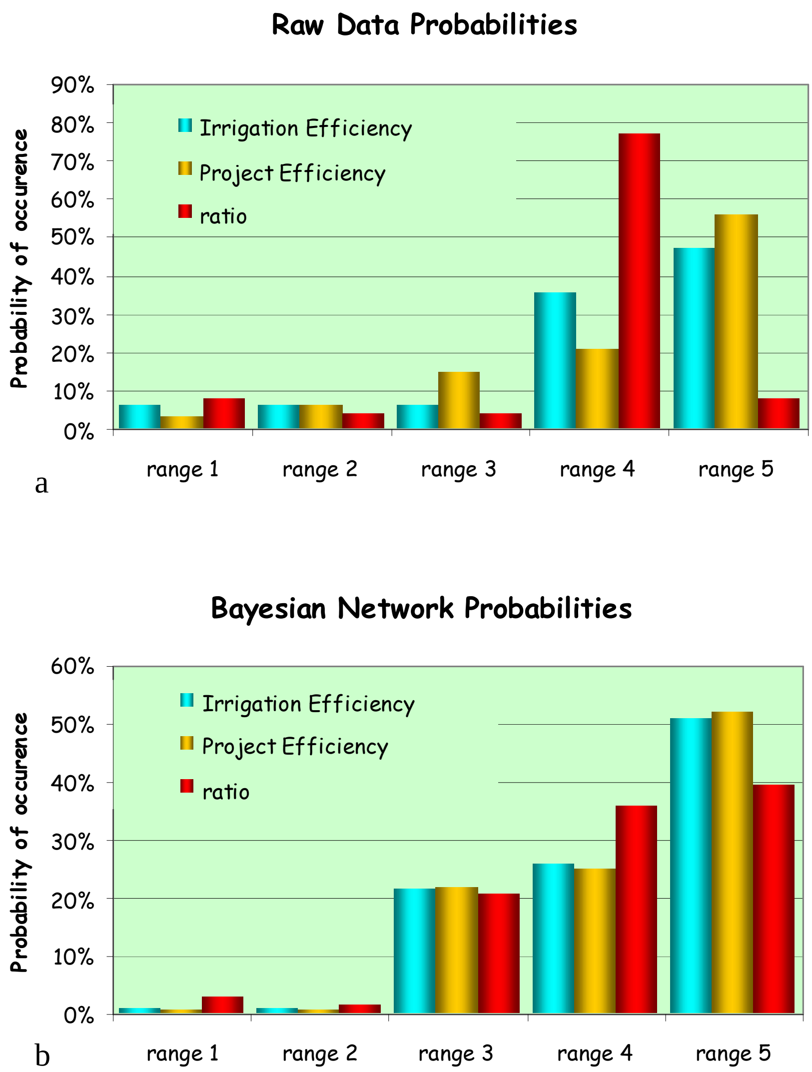


**Figure 9. Probability of occurence of measures of efficiency for raw data (a) and Bayesian Network beliefs (b).**

The time series constructed for the Burrendong dam releases (GL), tributary inflows (GL), catchment rainfall (mm), effective catchment rainfall (GL), reference evapotranspiration (mm), crop water use (mm), irrigation requirement (mm), change in ground water level (m), gauged river flows at Carinda (defined as end of system flows) (GL), irrigation diversions (GL), October water availability (GL), town water diversions (GL) and irrigation efficiencies (%) were used as the input into a Bayesian Network. This input was in the form of a case file with a value for each year comprising a row of data in the file. Missing data were identified by an asterisk.

The variables in the case file were used to construct the Bayesian Network nodes. Links were then made based on a subjective assessment of cause and effect (Table 4). Once these links were established the Bayesian Network was compiled (Figure 10).

The ranges used for each node in the Bayesian Network (Figure 10) are determined by identifying the maximum and minimum value for each variable and dividing by 5. This increment is rounded up to the next multiple of 5, 10, 50, 100, 200, 500 or 1000, as appropriate.

**Table 4. Relationships used to link the Bayesian Network water balance nodes.**

| Parent Node (cause) | Child Nodes (effect) | Reason |
|---|---|---|
| Total rainfall | Gauged tributary inflows | Rainfall is an average across the catchment and therefore will impact on the amount of runoff that becomes a tributary inflow and subsequently a contribution to the system flow. |
| | End of system flows | |
| | Total effective rainfall | The amount of precipitation that becomes effective rainfall (available for plant growth) is dependent on the total and the frequency and intensity of rainfall. |
| | Change in groundwater level | The amount of rainfall can have a direct effect on the change in groundwater levels. |
| Gauged tributary inflows | end of system flows | A proportion of inflow will become the end of system flow. |
| Dam releases | Irrigation and town water diversions | Water is released from the dam for these diversions (environmental flows can be equated to the end of system flows). |
| | End of system flows | |
| | Reference evapotranspiration | Evapotranspiration is included in this cause and effect relationship particularly to capture the effect of more releases on the evaporation component. |
| Evapotranspiration | Change in groundwater level | This link is included to capture the change in groundwater level that occurs across the catchment, not just the irrigation area. |
| | Crop water requirement | Evapotranspiration is an input into the modelled crop water requirement. |
| Total effective rainfall | Irrigation requirement | The irrigation requirement is the difference between the crop water requirement and the effective rainfall. |
| Crop water requirement | Irrigation requirement | |
| Irrigation requirement | Irrigation efficiency | This is to reflect the belief that in hot, dry seasons when the irrigation requirement is high and the water availability is low than the irrigation efficiency will be high. |
| Irrigation diversions | Irrigation efficiency | |
| Irrigation diversions | Change in groundwater level | To capture the losses to groundwater when the irrigation water is transported through the distribution channel or stored for later use. |
| Irrigation efficiency | End of system flows | Inefficiencies are caused by water supplied for irrigation being lost in surface water (end of system flows) or as deep drainage (change |
| | Change in | |

| | | |
|---|---|---|
| | groundwater level | in groundwater level) |

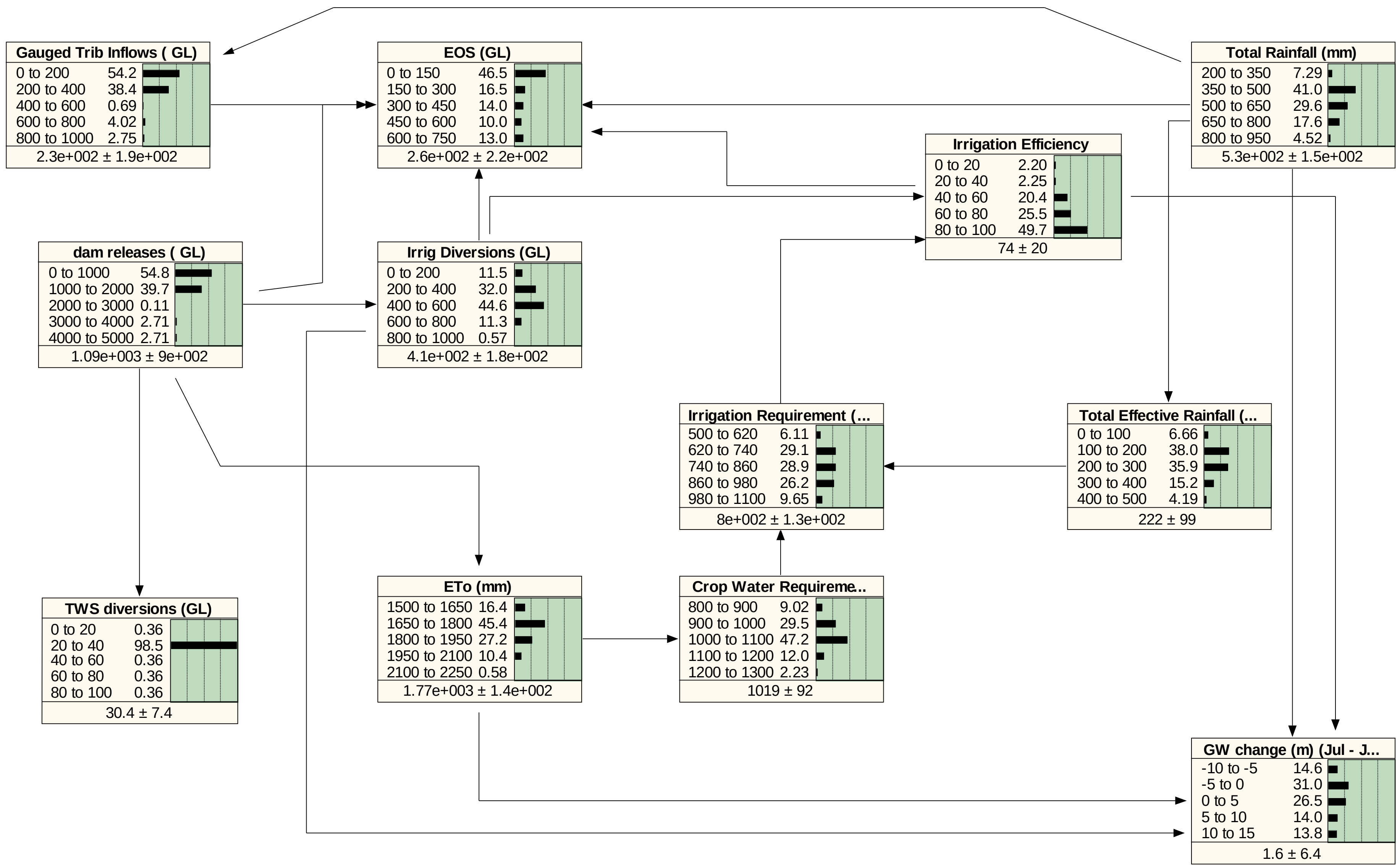


**Figure 10. Whole-of-System Irrigation Efficiency Bayesian Network.**

Cotton is the dominate crop irrigated in the Macquarie valley (see Appendix B) and there have been considerable measurements conducted at the field scale over recent years as part of the “Measure Water to Manage Water Initiative” using the Mobile Irrigation System Evaluation Unit. This unit was developed by the agricultural irrigation industry to assist irrigation farm managers to continue to improve irrigation techniques and minimise the impact of irrigated agriculture on the local environment.

Unpublished results obtained by measurement from the Mobile Irrigation system Evaluation Unit show that in one year, of the 19 evaluations undertaken, only 4 had an application efficiency > 50%. Comparison with the distribution of irrigation efficiencies reported in the Bayesian Network (Figure 10) suggest that the losses at the field scale are not reflected at the Whole-of-System scale.

### 6.5.4 Testing the water balance

A negative change in the ground water level indicates a rising water table. Therefore, it would be expected that less efficient irrigation would coincide with a greater chance of a rising water table (negative change from July to June) and more efficient irrigation with a greater chance of a falling water table (positive change from July to June). Similarly for rainfall, it would be expected that more rainfall would coincide with a rising water table and less rainfall with a falling water table.

An investigation of elements of the frameworks indicates that the above assumptions do not necessarily hold. Increasing rainfall does generally follow the expected pattern (**Figure 11** b – d), however when the there is a 100% probability that rainfall will be in the second highest range (**Figure 11** e), the probability of a small fall in groundwater (between 0 to 5m) increases to 60%. The reason for this was not investigated further in this study, but indicates the need to include all the variables that can impact on changes in groundwater levels. When there is a 100% chance that the rainfall is in the highest range the probabilities again reflect what is expected (an increased change of rising groundwater) (**Figure 11** f).

There was a <1% probability that the irrigation efficiency will be in the ranges 0% to 20% and 20% to 40% (Figure 11 g), therefore the results presented in Figure 11 h and i are based on limited values. When there is a 100% probability of irrigation efficiency being between 40% and 60%, there is a greater chance of a rising watertable (Figure 11 j), and when there is a 100% probability of irrigation efficiency being between 60 and 80% there is a greater chance of a falling watertable (Figure 11 k). The results for a 100% probability of an irrigation efficiency between 80% and 100% again are not as expected with a greater chance of a rising watertable. This again highlights the need to consider other impacts on the water balance.

It is, however, not a simple task to investigate all the variables that impact on the efficiency of system and because of the dynamic nature of these variables there are rarely clearly defined relationships. Simple linear regressions were applied to all the variables used in the construction of this water balance to highlight the difficulties in using causal relationships of just a few variables (Figure 12).

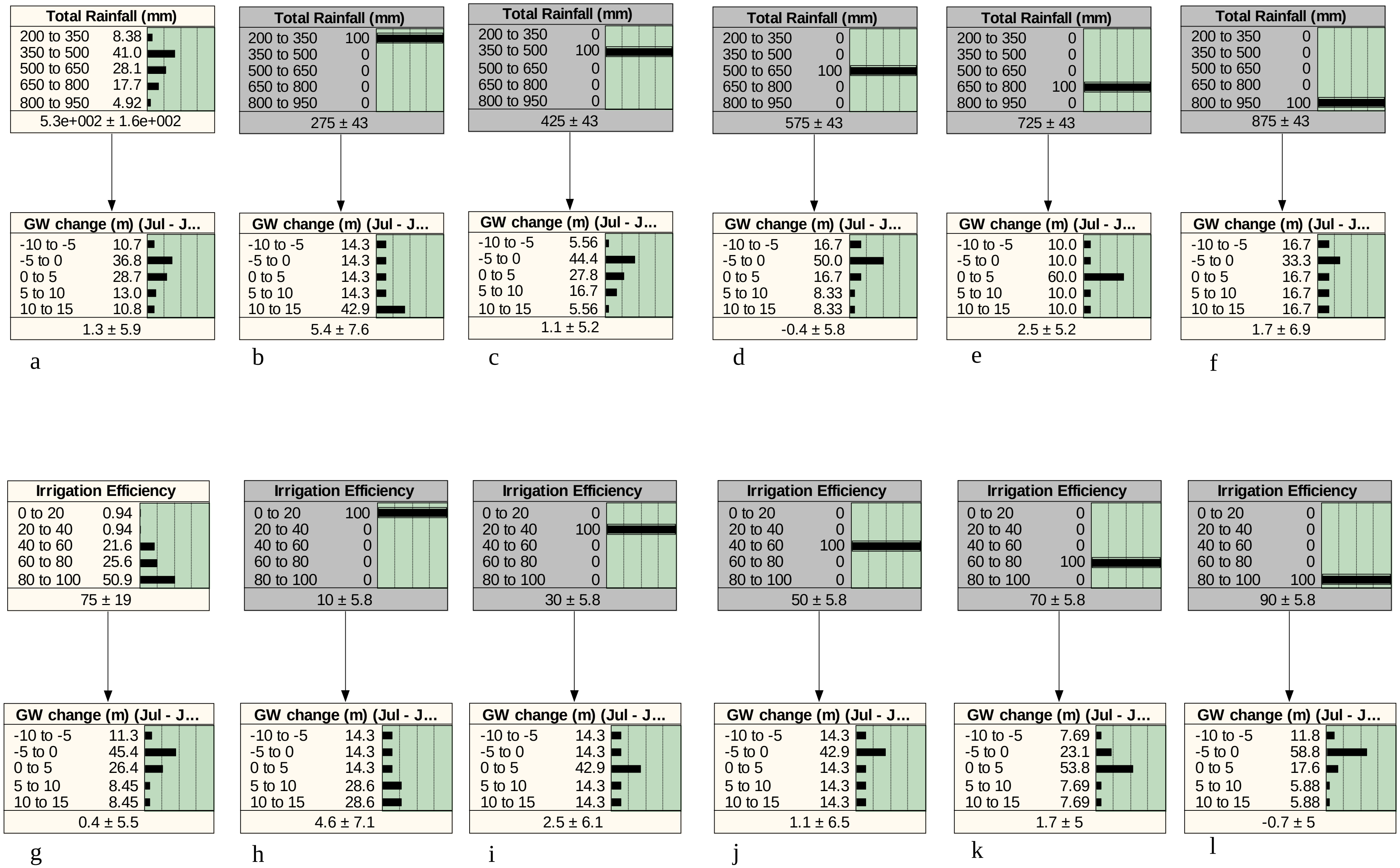


**Figure 11. Probabilities of Groundwater level changes as a function of ranges of rainfall (a-f) and ranges of irrigation efficiency (g-l)**

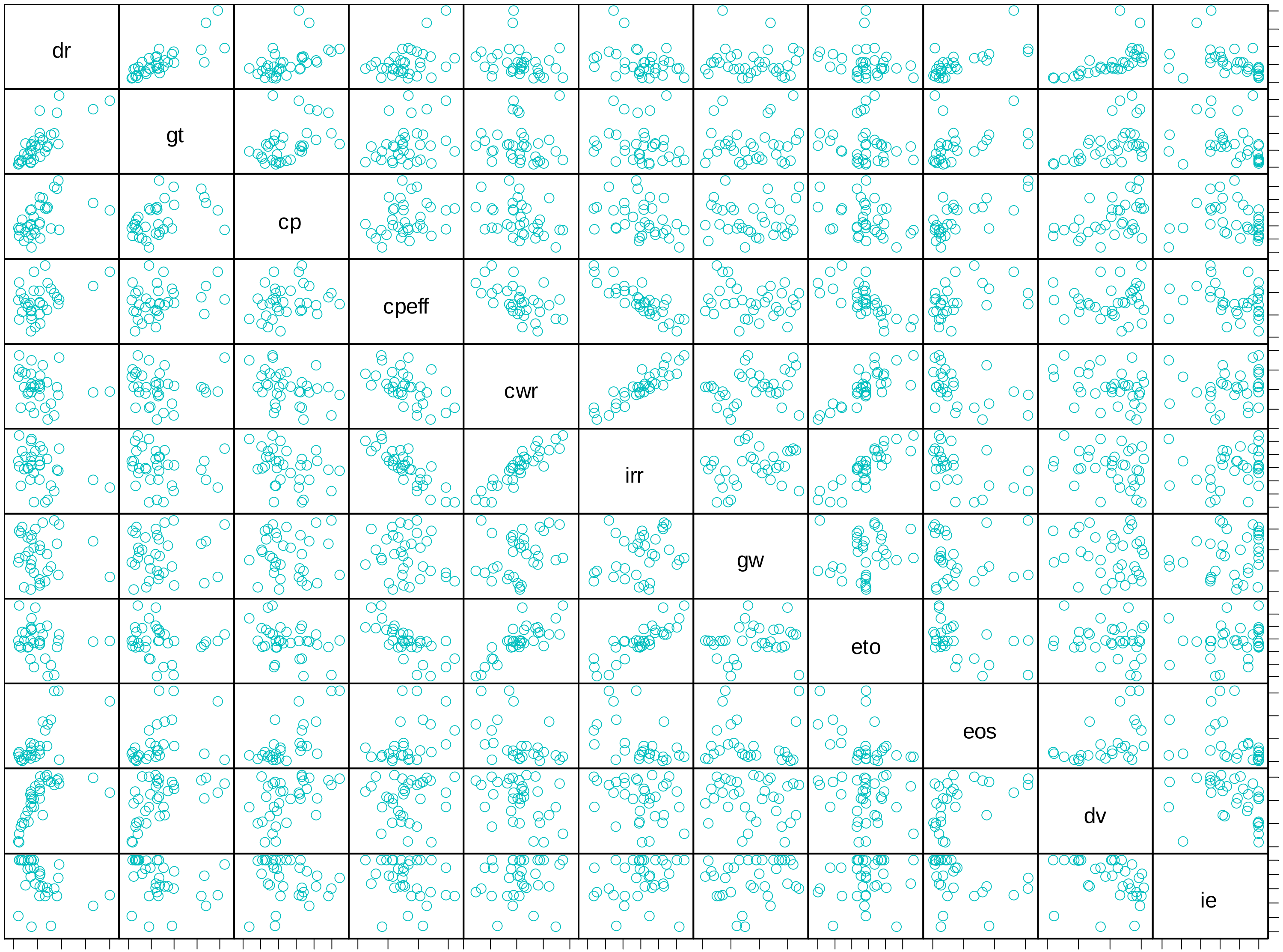


**Figure 12. Linear regressions applied to all the variables included in the water balance in a trellis plot. (dr = Burrendong dam releases (GL), gt = gauged tributary inflows (GL), cp = average total rainfall depth across the study area (mm), cpeff = average effective rainfall depth across the study area (mm), cwr = crop water requirements (mm), irr = irrigation requirements (mm), gw = groundwater level change (m), eto = reference evapotranspiration (mm),eos = end of system flows (GL), dv – irrigation diversion (GL) and ie = irrigation efficiency.**

It was indicated previously that the irrigation diversions and irrigation requirement were linked directly to irrigation efficiency based on the belief that in hot and dry seasons when irrigation requirements are high and water availability is low, irrigation efficiency is likely to increase. When these conditions are simulated in the Bayesian Network, by selecting 100% probabilities for low water availability (rainfall, tributary inflows, dam releases, irrigation diversion and end of system flows), high water requirements (ETo, crop water use and irrigation requirement) and a 100% probability of falling water tables there is a 10% increase in the probability that irrigation efficiency will be in the 80-100% range (Figure 13).

### 6.5.5 Sensitivity Analyses

Netica (Norsys 1998) includes a sensitivity analyses tool to test the expected reduction in variance of the expected real value of a parameter due to a finding at another parameter. The full sensitivity analysis of the Macquarie Valley Bayesian Network is provided at Appendix G. These results indicate the following order of sensitivity to changes in irrigation efficiency:

1. the annual change in ground water level (July to June),
2. end of system flows,
3. irrigation requirement,
4. crop water requirement,
5. irrigation diversions,
6. reference evapotranspiration,
7. dam releases.

These sensitivities are a function of the links and the direction of the links and therefore a full sensitivity analyses would require a comparison of these results with different links. There were insufficient time resources in this project to conduct this more complete sensitivity analyses, but it is an area for further investigation for any continuation of this work.

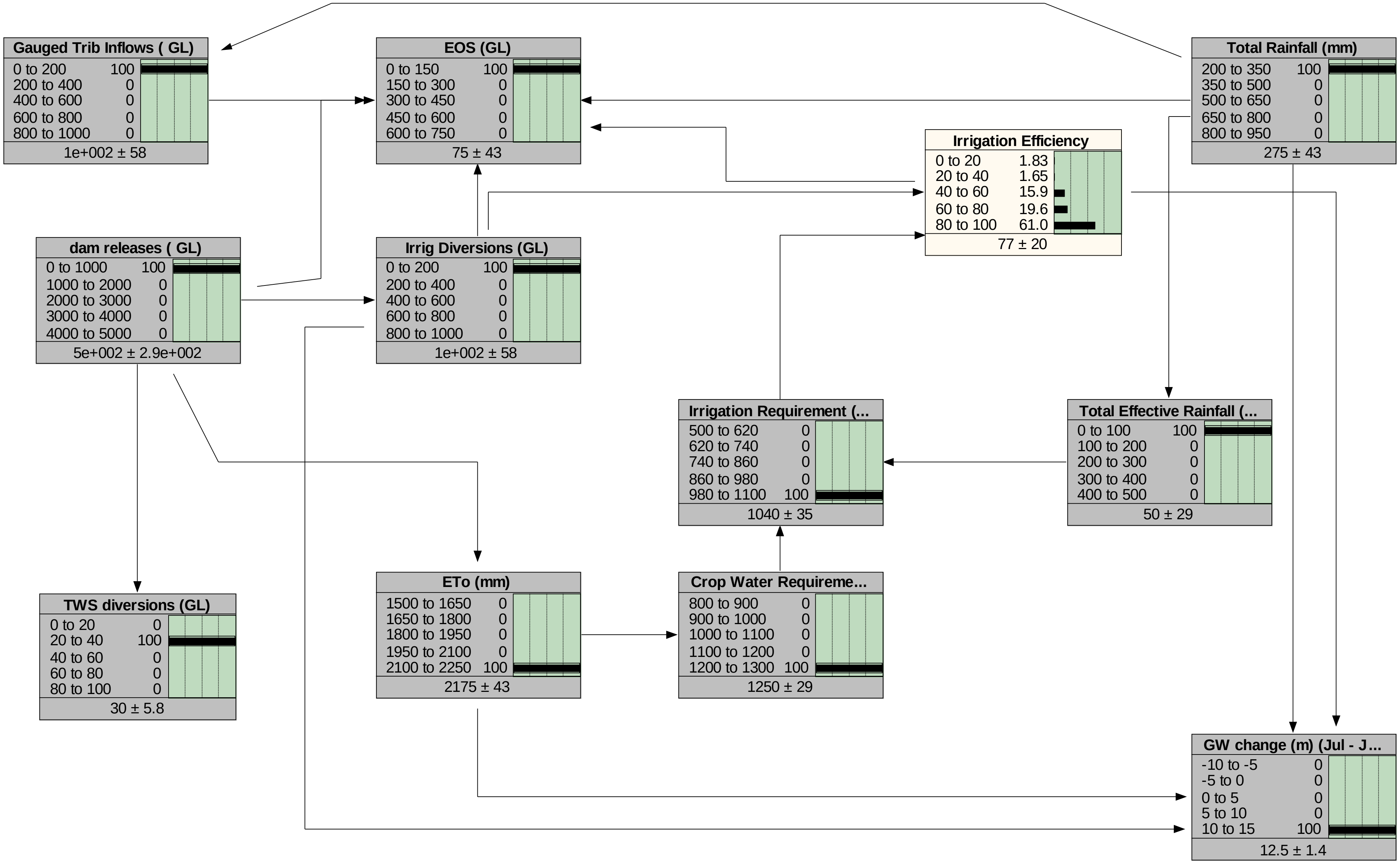


**Figure 13. The impact of a dry season (low water availability and high irrigation requirement) on irrigation efficiency.**

# 7 Conclusions

This project has explored the possibility of assessing Water Use Efficiency at the Whole-of-System scale. The initial methodology developed for this project was based on the traditional water balance, which requires that each element in the water balance be dimensionally equivalent. These traditional water balances were applied at the farm, scheme and catchment scales. By adopting a nested approach to linking the scales it was possible to identify the losses at one scale that may potentially be a gain at another scale.

The nested traditional water balances were used to construct Bayesian Networks and these networks were used to quantify the unaccounted for water at each of the scales. This approach was applied to both the Macquarie and Murrumbidgee valleys, though more data and validation is required before any degree of confidence can be placed in the results.

In an attempt to overcome the difficulties posed by utilising the traditional water balance a non-dimensional approach was adopted. The first step in this approach was to collate all the available data in a time series and use these data as the basis for constructing the Bayesian Network. This second methodology provided the flexibility to include variables with different dimensions (eg. depths and volumes) and also variables that are not explicitly included in the water balance but nevertheless have an influence (eg. reference evapotranspiration).

The second methodology was developed late in the project and was only applied to the Macquarie valley at a Whole-of-System scale. The results from this approach are preliminary in nature and more work is required to increase the degree of confidence in the output (eg. further sensitivity analyses).

As part of this project a literature and survey review was conducted on the factors that influence crop planting and watering behaviour. Due to time constraints, the results of this review have not been incorporated into any of the Bayesian Networks developed, but there inclusion is an area for future work.

# 8 Recommendations for further work

This project has provided the foundations for further work in the area of assessing Water Use Efficiency at a Whole-of-System scale using a Bayesian Network technique. Future work should integrate the nested spatial scale developed in the first methodology into the multi-dimensional approach developed in the second methodology.

The farm scale Bayesian Networks developed for this project do not necessarily reflect actual practices in the valleys. Future work should focus on collating this information and incorporating it along with results from the irrigator behaviour survey into the farm scale Bayesian Networks.

Stakeholders in each of the valleys have had very limited exposure to the Bayesian Networks and water balances developed for this project. Further work is required to test their reaction to the frameworks and capture their input through qualitative nodes in the Bayesian Networks.

If the methodologies developed in this project are to be developed for wider use a user friendly interface for the collation, modelling and analyses of data should be constructed. The development of this interface would enable the methodologies developed for assessing Water Use Efficiency at the Whole-of-System scale to be applied other valleys.

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ABS see Australian Bureau of Statistics

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## *APPENDIX A: WATER USE EFFICIENCIES AND INDICES*

Farm Total Water Use Efficiency (FTWUE): This is the measure of water used by the crop (ET) per available volume of water (Rainfall + Irrigation) during the year (%). Farm Total Water Use Efficiency (FTWUE) = water used by crop (ML)/ Rainfall + Irrigation (ML).

Farm Water Use Index (FWUI): This is the amount of crop produced per total water used at the farm level. The farm water use index can be calculated using total seasonal and irrigation water available and yield at farm level as (1) Farm Water Use Index ($FWUI_{season}$) = Total yield (kg) / Total seasonal water used (ML) and (2) Farm Water Use Index ($FWUI_{irrigation}$) = Total yield (kg) / Applied irrigation water (ML). These indices compare the yield of crop for the volume of water delivered or received (Hearn 1996). The volume of water includes irrigation and rainfall for $FWUI_{season}$ and irrigation for $FWUI_{irrigation}$. These indices are useful in comparison of the volume of water to produce a quantity of crop yield. However by the use of the "volume of water delivered" as the numerator implicitly means that these indices assume that water is the limiting resource in the production of the crop yield. If the farm water use index was compared and one was lower it may mean that nutrition or disease affected the crop yield, and it may not signify that the irrigation management was at fault. Production indicators overlap the two systems, the irrigation system and the agricultural system. The measurement of components of each system in a single index may suggest problems in either system but the index does not specify which system is at fault. It is therefore important to note that yield per megalitre of irrigation water may be used to assess the effectiveness of water use. However, achieving high yield is the basis of getting better production efficiencies and is not only about better farm water management but also better management of other farm aspects such nutrients, pest control, rotation, etc.

Crop Water Use Index (CWUI): This is the measure of yield produced per water used as evapotranspiration (ET) by a crop at farm level during the year. Crop Water Use Index (CWUI) = Crop yield (kg per ha) / Seasonal water used as ET (ML). This index is useful for assessing the water use index at crop level and most importantly to evaluate how efficient the crop produces yield with the amount of water consumed in terms of evapotranspiration during the growing period.

Crop Economic Water Use Index (CWUEI): This is also referred to as gross production water use efficiency and/or marginal irrigation economic water use index and measures the ratio of the value of irrigated agriculture production of the crop to the water delivered.

Conveyance Efficiency (CE): This is the efficiency of the scheme system to deliver water to the farm, i.e., the amount of water released from scheme storages (or diverted from the catchment river) and the amount of water received at farm gate as a percentage. Conveyance Efficiency (%) = Water received at farm gate/ Water released (Raine 1999).

Overall System Efficiency (OSE): This is the ratio of the total amount of water in the catchment to the amount of water delivered or available to the crop.

### *APPENDIX B: WATER BALANCE FRAMEWORKS FOR INITIAL METHODOLGY.*

**Spatial and temporal boundaries.**

*CATCHMENT SCALE*

For the method of applying a traditional water balance, the spatial boundaries for the catchment water balance were identified as below the dam wall to the terminal of the river, and the watershed boundary for the river of interest. The terminal of the river was determined as a point where end of system flows could be isolated for the particular watershed being studied. This tight water balance boundary is required to handle the uncertainty associated with flows in other rivers in the greater catchment.

The temporal scale for the catchment water balance was based on the 12 months water year, July to June. This is because data on water usage is reported over this period the Department of Infrastructure, Planning and Natural Resources (O'Neil and Pearce 2004). However, it is important to note that the catchment level temporal scale must encompass changes in catchment streamflow and should be linked to changes in the climate, for example, one complete El Nino La Nina cycle. This temporal scale may range over one to five years or longer. However, in this project, no changes in catchment streamflow and linkages to changes in the climate were studied. These were considered beyond the scope of the work undertaken for this project.

## Macquarie Catchment

The Macquarie catchment is in the central west of New South Wales (Figure B. 1). The Macquarie catchment is one of the three smaller catchments, that is, Castlereagh, Macquarie and Bogan catchment that form the NSW Central West (Greater Macquarie) catchment as part of the Murray Darling Basin (MDB).

The spatial boundaries for the study area within the Macqaurie catchment are from below the Burrendong dam to the end of flow measuring station near the Macquarie Marshes located about 80 km north of the township of Warren at Carinda (Figure B. 1). The catchment study area was calculated to be approximately 25,620 $km^2$ (2,562,000 ha) which represents around 35% of the whole Macquarie catchment that covers an area of 73,000 $km^2$ (ABS 1997, DLWC 2003) and 28% of the whole Central West catchment of 92,200 $km^2$. The temporal scale for the catchment water balance is the 12 months water year, July to June.

The construction of the Burrendong dam was completed in 1967 and is sited above Wellington at the confluence of the Cudgegong and the Macquarie rivers. This dam is the major regulatory structure in the valley and has a total storage capacity of up to 1,680 GL of water. The Macquarie Marshes are a series of wetlands consisting of a complex system of poorly drained depressions, lagoons and branching channels.

The irrigation industry in the Macquarie catchment is the most developed in the NSW Central West Catchment. Of the 1,150,000 ha of land irrigated in NSW, approximately 5% or 56,000 ha is in the Central West (Greater Macquarie) catchment. Most of this is concentrated around the regulated portions of the Macquarie and Cudgegong rivers in the Macquarie catchment (ABS 1997). It has been estimated that 30% of the Macquarie catchment's value of agricultural production comes from irrigation of 1% of the total land (Martin 2003). The dominant irrigated crop in Macquarie catchment is cotton and represents approximately half the total area irrigated from regulated supplies. The Macquarie catchment is the third largest cotton-producing area in Australia (Hearn and Cameron 1997). Many other crops such as vegetables, wheat, pastures, citrus, lucerne, soybean, barley etc are also grown in the catchment.

In the Macquarie catchment, most irrigated crops are watered using surface methods (ABARE 1998). Salinity and waterlogging are the major threats to the irrigation industries in this catchment. Watertables have been rising in the Lower Macquarie catchment since the late 1980s (Willis and Black 1996; Willis and Hulme 1996; Water Resources Commission 1987). Willis and Black (1996) suggest that irrigation may contribute to this phenomenon. Waterlogging and associated salinisation have been identified in parts of the Macquarie catchment and potential risk areas have been mapped.


**Figure B. 1.  Map of the Macquarie catchment.**

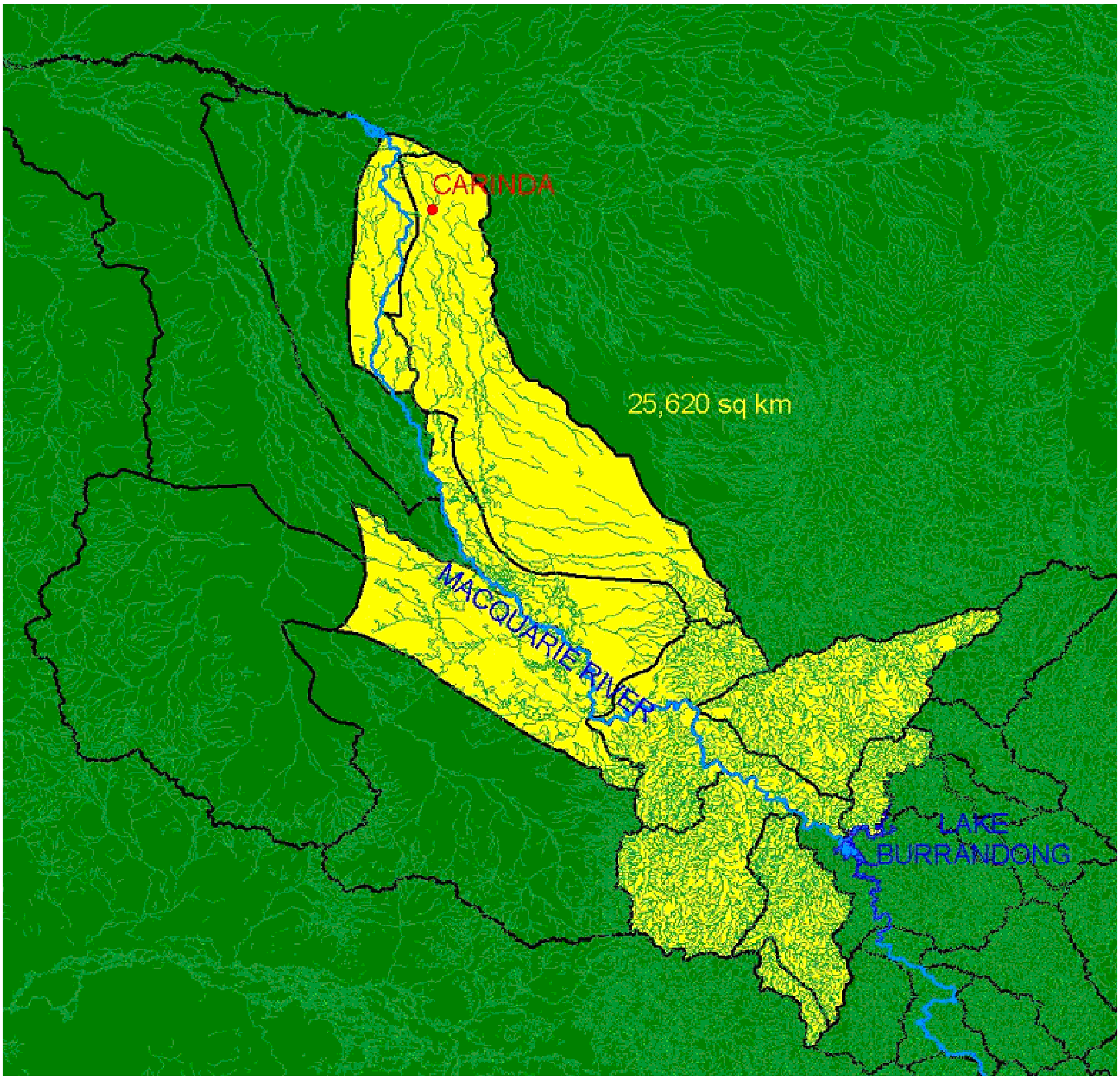


**Figure B. 2. Map of the Macquarie catchment showing the location and spatial boundaries of the study area.**

***Provided by Udai Pradhan, Spatial Information Officer, NSW DPI, Orange, 2004.***

## Murrumbidgee Catchment

The Murrumbidgee catchment is located in southern New South Wales and is part of the Murray Darling Basin (MDB) (Figure 3.3). The Murrumbidgee catchment is divided into four zones, that is, the upper, mid and lower catchment and the Murray catchment management board area.

The spatial boundaries for the study area in the Murrumbidgee catchement are from below the Burrinjuck and Blowering dams to the end of flow measuring station in the lower catchment at Balranald (Figure 3.4). The catchment study area was calculated to be approximately 64,125 $km^2$ (6,412,500 ha) which represents around 76% of the whole Murrumbidgee of 84,000 $km^2$ and 6% of the Murray – Darling Basin that cover an area of approximately 1,050,000 $km^2$ (Hope 2003).

The combined total storage capacity of Burrinjuck and Blowering dams within the Murrumbidgee catchment for all purposes is 2,658,000 ML with 1,026,000 ML for Burrinjuck dam on the Murrumbidgee River and 1,632,000 ML for Blowering dam on the Tumut River. Water is stored in

Burrinjuck and Blowering dams during winter and then used to supply irrigation farms downstream during summer.

The upper catchment includes the western slopes of the great dividing ranges between Lake George and Burrinjuck Dam. The watercourse twists around the Australian Capital Territory (ACT) past the towns of Adaminaby, Cooma, Bredbo and the city f Canberra before draining into Burrinjuck Dam. Burrinjuck Dam also receives water from the Yass, Molonglo and Goodradigbee rivers. Water flows into the Murrumbidgee river and used to support irrigated agriculture (Scoccimarro et al. 1997) and other purposes.

The mid catchment includes the section of river from Burrinjuck Dam to just downstream of Wagga Wagga. Water from the Tumut River is captured in Talbingo Dam and then Blowering Dam for release to downstream industrial, irrigation, stock and domestic and town water supplies. The mid catchment is characterised by undulating landscape and fertile alluvial floodplains adjacent to the watercourse. Towns in this area include Cootamundra, Tumut and Wagga Wagga. Wheat, canola, pasture, barley and legumes are grown on the red earth soils around Wagga Wagga. The area supports lucerne production and pasture for dairying on the alluvial soils close to the river.

The lower catchment includes the section of river downstream of Wagga Wagga to Balranald and is characterised by flat landscapes (slope < 1%) with broad, fertile alluvial floodplains. Towns in this area include Narrandera, Leeton, Griffith, Hay and Balranald. The former Murrumbidgee Irrigation Area (MIA) and Coleambally Irrigation Area (CIA) are also in this section. In the lower catchment, a wide variety of crops is grown along the river. Rice is cultivated around Darlington Point, Carrathool and Hay where there are heavy clay soils. Maize, soybeans, canola, lucerne, sunflowers, safflower, cereals and pasture are also grown on farms close to the river. Vegetables, citrus and other permanent plantings and are grown on the lighter soils or on the old sand hill formations in this part of the catchment (DWR 1987).

The Murray catchment management committee area lies south of the mid and lower Murrumbidgee catchment areas. This region could be in either the Murrumbidgee or Murray catchment. For licensing purposes, the area is considered part of the Murrumbidgee catchment, but, for water management purposes, the area is considered part of the Murray catchment (Hope 2003).

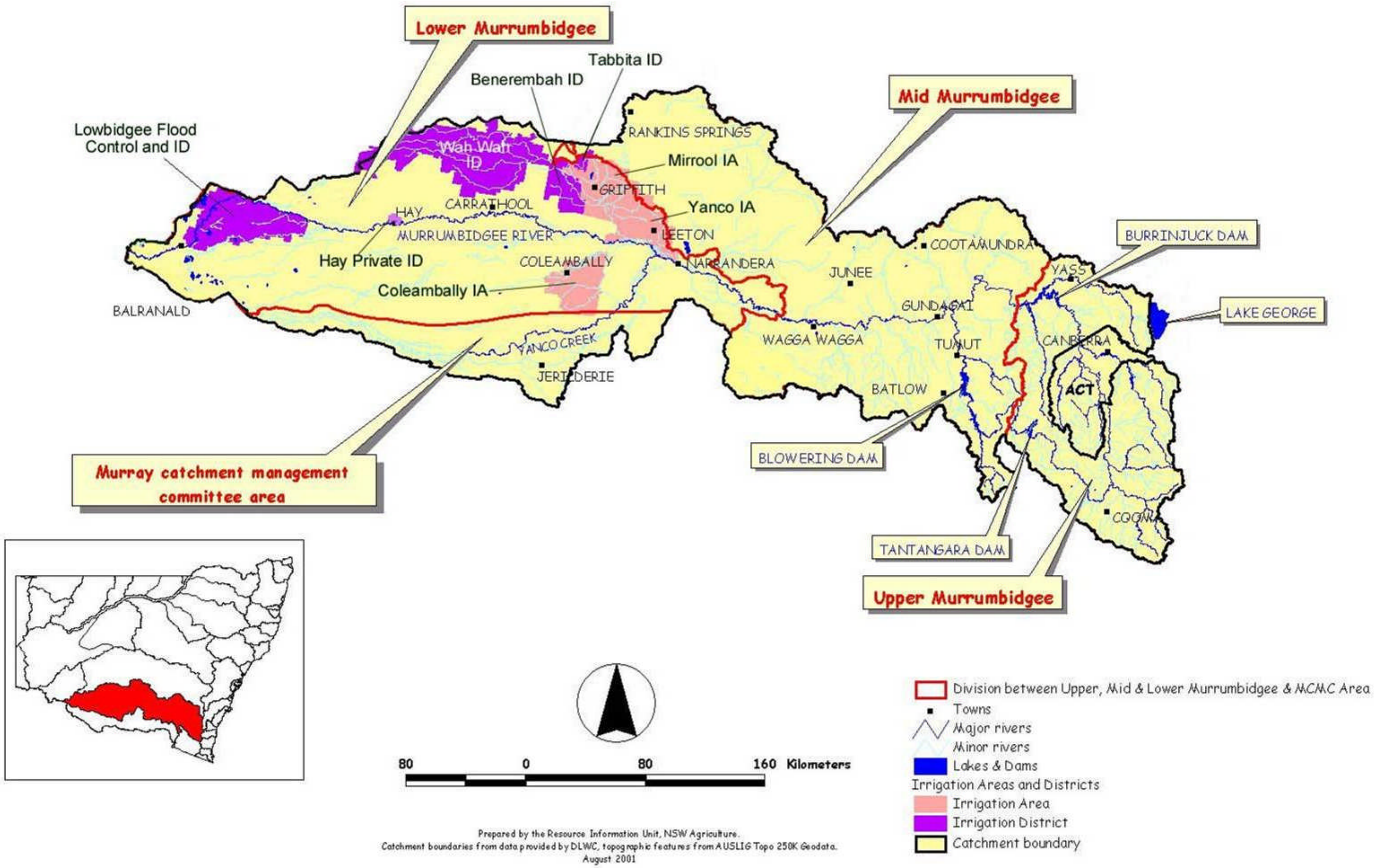


**Figure B. 3. Map of the Murrumbidgee catchment.**

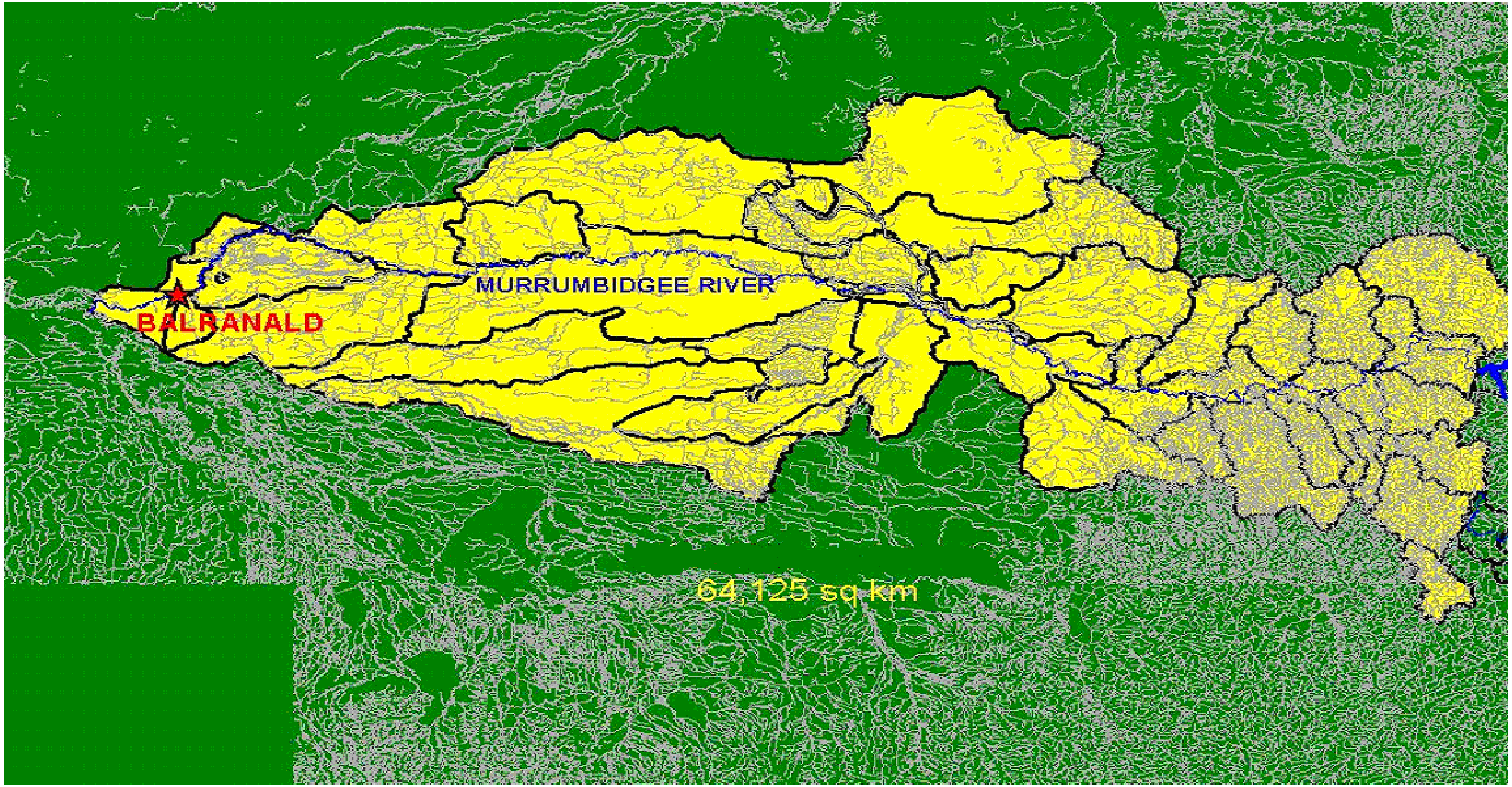


**Figure B. 4. Map of the Murrumbidgee catchment showing the location of the study area.**

***Provided by Udai Pradhan, Spatial Information Officer, NSW DPI, Orange, 2004.***

### *SCHEME SCALE*

Scheme refers to the respective irrigation region, area or district within the valleys. There are seven off-river irrigation schemes in the Macquarie river valley and technically three irrigation areas (districts) in the Murrumbidgee river valley. The spatial boundaries of the scheme scale water balance were identified as where water was diverted from the river, and scheme channels. Schemes usually record and report water use that coincides with the allocation rules for the valley and operate over a period of 12 months. For this reason, the temporal scale for scheme scale is over a one year time period.

## Macquarie Schemes

The seven off-river irrigation schemes within the Macquarie river valley study area are the Narromine, Buddah Lakes, Tenandra, Trangie–Nevertire, Greenhide, Marthaguy and Nevertire schemes (Table B. 1). The following is a summary of the survey that was conducted on these irrigation schemes of the Macquarie river valley. The survey specifically aimed at recording the history, location, size and management practices of the schemes (Elliot 1995). The summaries vary in the level of detail and information that has been included.

Narromine irrigation scheme (NIS): NIS was established in 1970 and supplies water from the Macquarie river to irrigate properties (farms) located in the westerly direction of Narromine. The irrigation lay-out is by border-check or furrow and crops such as cotton, lucerne, soybean, wheat, pasture and nursery plants are grown. The total scheme allocation is 60,110 ML/year in a year of 100% allocation from Burrendong dam and allocation of each member is measured from the scheme channel onto the farm through dethridge wheels. Off-allocation flows are utilised by scheme when available. The major operating expense is electricity for pumping water. The scheme covers an area of 120,000 ha.

Buddah lakes irrigation scheme (BLIS): BLIS was completed in 1969 and supplies water immediately downstream of Narromine to properties (farms) located to the east of Mitchell Highway between Narromine and Trangie. The total scheme allocation is 32,508 ML/year in a year of 100% allocation from Burrendong dam and diversions by members are measured by flow meters installed at members' outlets. All properties on the scheme have some form of tailwater recirculation system. Crops such as cotton, pasture, wheat, corn, barley and oats are grown. The total allocation of the scheme is fully utilised. The scheme covers an area of approximately 17,000 ha.

Tenandra irrigation scheme (TIS): TIS commenced in 1969 and supplies water from the Macquarie river upstream of the Gin Gin Weir for irrigation, stock and domestic purposes on the eastern side of the river, commencing at Gin Gin and extending north of Warren. The irrigation is by border-check or furrow depending on the crops grown. Crops such as cotton, lucerne, wheat, pasture and sorghum are grown. A total of 34,800 Ml/year is available in a year of 100% allocation from Burrendong dam. Off-allocation flows are purchased by the scheme and sold to all members when available.

Trangie–Nevertire irrigation scheme (TNIS): TNIS was completed in 1973 and supplies water from the Macquarie river to irrigate properties (farms) located to the west of Trangie. The irrigation is by border-check or furrow depending on the crops grown. Crops such as cotton, lucerne, wheat, pasture and oats are grown. A total of 63,510 Ml/year is available in a year of 100% allocation from Burrendong dam. The diversions of each member are measured by channel attendants using hand held flow meters. Off-allocation flows are utilised by scheme when available. The scheme covers an area of 102,000 ha.

Greenhide irrigation scheme (GIS): GIS commenced operation in 1969 and supplies water from the Macquarie river downstream of the Gin Gin Weir for irrigation purposes to properties from Gin Gin bridge to 20 km north of the river in direction of the township of Collie. Crops such as pasture, lucerne, cotton, and sorghum are grown. The irrigation is by border-check or furrow depending on the crops grown. A total of 7,840 Ml/year is available to ten licenced properties on the scheme. Off-allocation flows are purchased directly by members when available. The irrigation area of the scheme is approximately 835 ha developed for irrigation.

Marthaguy irrigation scheme (MIS): MIS was completed in 1988 and supplies water from the Macquarie river to irrigate properties in the Marthaguy district. The irrigation is by border-check or furrow depending on the crops grown. Crops such as cotton, wheat, soybeans, barley and oats are grown. The diversions of individual properties are measured hand held flow meters. Off-allocation flows are utilised by scheme when available. The scheme has an area of approximately 3,500 ha developed for irrigation.

Nevertire irrigation scheme (NTIS): NTIS was established in 1968 and supplies water from the Macquarie river to irrigate properties in the “Snake Plain” area between Warren and Nevertire on the western side of the river. All water delivered by the scheme is used for flood irrigation. Crops such as cotton, lucerne, wheat, pasture and corn are grown. The allocation is 32,000 ML for irrigation. Members’ allocation can be enhanced by access to off-allocation flows consistent with other irrigators in the Macquarie valley.

It should be noted however that in addition to the off-river schemes, there are riparian irrigators in the Macquarie catchment and the number of members is estimated to be approximately 600 with an entitlement of about 394,400 ML (Hope 2003).

## Murrumbidgee Schemes

The irrigation schemes and/or areas in the Murrumbidgee river valley can be grouped into three categories, that is, Murrumbidgee Irrigation Area (MIA), Coleambally Irrigation Area (CIA) and Hay Irrigation Area (HIA) as shown in Table B. 2. (Hope 2003) stated that technically, MIA and CIA lands no longer exist and the land is now operated by Murrumbidgee Irrigation and Coleambally Irrigation Co-operative Limited, however, since the terms are still in common usage, this project will continue to refer to them. The following is a summary of the survey that was conducted on these irrigation schemes over which the developed water balance framework have been applied within the Murrumbidgee catchment.

Yanco irrigation area (part of the MIA): Yanco irrigation area was established in 1912 and the area is 88,760 ha of which approximately 70% is irrigated annually. Rice is now one of the major commodities cultivated in this area (MIA & D LWMP WG 1997). Horticulture, dairying and pasture are also grown.

Mirrool irrigation area (part of the MIA): Mirrool irrigation area was developed in 1924 and supports approximately 1173 farms and around 70% of this area is irrigated.

Benerembah irrigation district (part of the MIA): Benerembah irrigation district was established in 1933 to use the drainage water from Yanco and Mirrool irrigation areas. The District, to the south-west of Griffith, was initially established to supply water to stock and domestic licence holders. Benerembah has 138 farms and a total scheme area of 44 235 ha. Around 80% of this land is irrigated.

Tabbita irrigation district (part of the MIA): Tabbita irrigation district was also developed in 1933 and is small compared to the other Areas and Districts, with only 22 farms. The District has a total area of 10 473 ha and just under half of this is irrigated.

Wah Wah irrigation district (part of the MIA): Wah Wah irrigation district was developed in 1930, the district was also created to use the drainage water from Yanco and Mirrool irrigation areas and to supply the water to stock and domestic licence holders. The district has a total scheme area of 261 955 ha but only 7% of this is irrigated.

Coleambally irrigation area (CIA): Coleambally irrigation area was established as a government-owned enterprise to utilise this new water resource. Unlike the MIA, the CIA refers to one area only; it has its own arterial supply and drainage canal network. The CIA is located 60 km south of the city of Griffith. The total scheme area is 79 161 ha and around 95% of this is irrigated. The CIA is a predominantly rice-based and supplements income with soybeans, winter cereals, sheep, wool and limited horticultural products such as grapes, prunes and vegetables. There are 345 farms and, of these, 12 were designated for horticulture purposes. There are now 39 horticultural designated farms (CICL Unpublished).

Hay irrigation district (HIA): Hay irrigation district was set up in 1913. The area was initially used for fodder and dairy production (hallows and Thompson 1995).there are approximately 64 farms. The total scheme area is about 2, 460 ha and under half of it is irrigated.

**Table B. 1. Description of irrigation schemes in the Macquarie valley.**

| Irrigation scheme | Year Established | Total Scheme Area (ha) | Total Allocation (ML/year) | Number of Members | Length of Channel (Km) | Total Area of Channel (ha) | Total Area Irrigated (ha) |
|---|---|---|---|---|---|---|---|
| Narromine | 1970 | 120,000 | 60,100 | 94 | 350 | 175 | 10,000 |
| Trangie–Nevertire | 1973 | 102,000 | 63,500 | 66 | 250 | 125 | 12,000 |
| Tenandra | 1969 – 72 | NA | 34,800 | 32 | 150 | 75 | 7,000 |
| Buddah Lakes | 1969 | 17,000 | 32,500 | 19 | 58 | 29 | 4,200 |
| Marthaguy | 1988 | NA | 16,600 | 16 | 60 | 30 | 3,500 |
| Nevertire | 1968 | NA | 32,000 | 15 | 50 | 25 | 4,150 |
| Greenhide | 1969 | NA | 7,840 | 10 | 30 | 15 | 835 |
| **Total** | | | **247,340** | **248** | **948** | **474** | **41,685** |

*Source: Irrigation Farming in the Macquarie Valley (Elliot 1995), Russ 1999; Wolfgang 1998; NA = Not available; It was assumed that the average wetted perimeter (seepage face) of the channel is 5m.*

**Table B. 2. Description of irrigation areas and districts in the Murrumbidgee valley.**

| Historical Name | Irrigation Area or District | Year Established | Total Area of Scheme (ha) | No. of Farms | Length of Channel (Km) | Total Area of Channel (ha) | Total Area Irrigated (ha) |
|---|---|---|---|---|---|---|---|
| MIA | Yanco Irrigation Area | 1912 | 88,760 | 1,173 | 2010 | 1005 | 62,132 |
| MIA | Mirool Irrigation Area | 1924 | 74,791 | 1,249 | | | 52,354 |
| MIA | Benerembal Irrigation District | 1933 | 44,235 | 138 | | | 35,388 |
| MIA | Tabbita Irrigation District | 1933 | 10,473 | 22 | | | <5,236 |
| MIA | Wah Wah Irrigation District | 1930 | 261,955 | 151 | | | 18,337 |
| CIA | Coleambally Irrigation Area | 1960 | 79,161 | 345 | 516 | 258 | 75,203 |
| HIA | Hay Irrigation Area | 1913 | 2,460 | 64 | NA | NA | <1,230 |
| **Total** | | | **561,835** | **3,142** | **2,526** | **1,263** | **243,414** |

*Source: Murrumbidgee Catchment Irrigation Profile (Hope 2002), NA = Not available; It was assumed that the average wetted perimeter (seepage face) of the channel is 5 m.*

### *FARM SCALE*

There are many farms that vary in size within the Macquarie and Murrumbidgee valleys. The spatial boundaries for the farm scale water balance were identified as where water was received at the farm gate to the fields. The temporal scale for the farm level is linked directly to the growing season as well as incorporating the ability to capture overland flows and off allocations. Therefore, the temporal scale for farm level is over a one year time period.

In the Macquarie valley, irrigation farms can be found either along the fertile riverine plains and slopes close to the Macquarie river or in the seven off-river irrigation schemes of Narromine, Trangie–Nevertire, Tenandra, Buddah Lakes, Marthaguy, Nevertire and Greenhide. In the Murrumbidgee valley, all the irrigation farms in the areas and districts are also distributed along the entire length of the Murrumbidgee river.

## Developing the Water Balance Frameworks

A stepwise process was followed to develop the initial framework for assessing whole of system water use efficiency for this project. The framework is based on water balances at three nested and linked spatial scales (i.e. catchment, scheme and farm). The water balance frameworks at each scale were developed by assessing the incoming and outgoing water flux into and from each scale during the temporal scale period. Elements that were considered in constructing the water balances included accounted for water (flow or water that is wholly accounted for in the water balance), partially accounted for water (flow or water information is partially known and only the known water is accounted for in the water balance) and unaccounted for water (flow or water that is unknown and not accounted for in the water balance).

However, it has to be borne in mind that even though the accounted for water can be either measured or predicted with reasonable accuracy there are error bands that should be quantified and these error bands increase considerably with the partially accounted for and unaccounted for water. This uncertainty is an important part of characterising a water balance.

The following generic water balance equation is taken from the work of the previous research officer for this project (Mitchell 2002) to be applied at each of the scales:

**P + SWin + CR = SWout + DD + ET + DS**

Where

P = Rainfall
$SW_{in}$ = Surface Water flowing in to the system
CR = Capillary Rise
$SW_{out}$ = Surface Water flowing out of the system
DD = Deep Drainage
ET = Evapotranspiration
$\Delta S$ = Change in Storage.

It is acknowledged that for each scale water is transported upwards by capillary rise (CR) from shallow water table or transferred horizontally by subsurface flow in ($SF_{in}$) or out ($SF_{out}$) of the root zone. Capillary rise is the ability of soil water to penetrate upwards into fine pores and cracks of soils. However, in many situations, these are minor and were considered negligible and/or beyond the scope of the work undertaken for this project.

## Catchment Water Balance Framework

The components of the water balance for catchment scale were identified and the water balance framework constructed based on the spatial boundaries and by assessing the incoming and outgoing water flux into and from each scale over a specified time period. Any surface water that entered the river system (e.g. dam releases and tributary inflow) is deemed as surface water inputs to the catchment system. Surface water that left the catchment system (e.g. illegal extraction and end of system flows) is considered as surface water outputs. Groundwater (total amount of water from the ground that enters and/or leaves the catchment) can be either an input or output depending on whether the system is a receiving or losing catchment river system. Substituting the surface water inputs and surface water outputs into the generic equation above we obtain the following water balance equation for the catchment scale:

$$\mathbf{P + DR + TI = ET + GW + EOS + IE + E + DD + \Delta S +/- M/O\ E} \qquad \textbf{(1)}$$

Where

P = Rainfall
DR = Dam Releases
TI = Tributary Inflow
ET = Evapotranspiration
E = Evaporation
DD = Deep Drainage
GW = Ground Water
EOS = End Of System
IE = Illegal Extractions
ΔS = Change in Soil Moisture.
M/O E = Measurement or Operational Error

For the purpose of this project, the catchment's unaccounted for water (CUW) is defined as the difference between the sum of the volume of input water and the sum of the quantified water outputs (volume of water diverted for irrigation and end of system flows). The CUW includes evapotranspiration (total amount of water used by the crop across the catchment during the year, it includes evaporation from the bare soil and transpiration via the plant (mm), evaporation (total amount of water lost from the water surfaces of the river system during the year), deep drainage (total amount of water lost due to drainage from the catchment during the year), ground water (total amount of water from the ground that enters and/or leaves the catchment during the year), illegal extraction (total amount of water taken from the catchment without licence during the year) and change in soil moisture (the difference between the final and initial total amount of moisture that is stored in the soil in the root zone in the catchment over a specified profile depth during the water year).

Substituting CUW into equation (2) above we obtain:

$$\mathbf{CUW = P + DR + TI - EOS +/- M/O\ E} \qquad (2)$$

Where

CUW = Catchment's unaccounted for water is the difference between the sum of the volume of input water and the sum of the quantified water outputs.

P = Rainfall is the total amount of water from rain that falls on the surface of the catchment during the year.

DR = Dam releases is the total amount of water released by the dam into the catchment during the year.

TI = Tributary inflow is the total amount of water that enters the catchment from the tributaries during the year.

EOS = End of system flows is total amount of water that is uncommitted and/or environmental flows at the determined end point of the catchment during the year.

M/O E = Measurement of error is the estimate of amount of error that occurs due to measurement and can apply as both an input and an output.

Equation (2) can be used to calculate the CUW at the catchment scale and for the assessment of water use efficiency. If there was a volume of unaccounted water then the processes that lead to this loss can be identified. Units for all variables are in gigalitres (GL) or megalitres (ML).

## Scheme Water Balance Framework

The scheme scale water balance framework was developed by assessing the water into the scheme storage and water released from scheme storage over the water year. Any surface water that entered the scheme (e.g. diversions, scheme storage and ground water) is deemed as surface water inputs to the scheme system. Surface water that left the scheme (e.g. deliveries, illegal extraction and end of system flows) is considered as surface water outputs. Substituting the surface water inputs and surface water outputs into the generic equation we obtain the following water balance equation for the scheme scale:

$$P + DV + SS + GW = DL + EOS + IE + DD + E + \Delta S \pm M/O\ E \quad (3)$$

Where

P = Rainfall
DV = Diversions
SS = Scheme Storage
GW = Ground Water
DD = Deep Drainage
DL = Deliveries
EOS = End of System Flows
IE = Illegal Extractions
E = Evaporation
ΔS = Change in Soil Moisture.
M/O E = Measurement or Operational Error

The scheme's unaccounted for water (SUW) is defined as the difference between the volume of water input (rainfall additions plus the volume of water diverted from the river system) and the volume of water delivered to the farms. The SUW includes evaporation (total amount of water lost from the water surfaces of the scheme delivery channels and/or on-scheme storage during the year), deep drainage (total amount of water lost due to drainage from the scheme and/or leaves the delivery channels and on-scheme storages through the soil during the year), end of system (the total amount of water that is uncommitted or environmental flows at the determined end point of the scheme during the year (if applicable)), groundwater (total amount of water from the ground that enters the scheme during the year), illegal extraction (total amount of water taken unlawfully from the delivery channel of the scheme during the year (if applicable)) and change in soil moisture (the difference between the final and initial total amount of moisture that is stored in the soil of the delivery channels and on-scheme storages within the scheme during the year).

Substituting SUW into equation (3) we arrive at:

$$SUW = P + DV - DL \pm M/O\ E \quad (4)$$

Where

SUW = Scheme's unaccounted for water is the difference between the volume of water input (rainfall additions plus the volume of water diverted from the river system) and the volume of water delivered to the farms.

P = Rainfall is the total amount of water from rain that falls on the surface of the scheme channels during the year.

DV = Diversions is the total amount of water diverted from the river system to the scheme during the year.

DL = Deliveries is the total amount of water that is delivered to the farm gate from the scheme during the year. It includes on scheme storages (the total amount of water that is stored on the scheme at the beginning of the year (if applicable).

M/O E = Measurement of error is the estimate of amount of error that occurs due to measurement and can apply as both an input and an output.

Equation (4) can be used to calculate the catchment's unaccounted for water for the scheme scale and for the assessment of water use efficiency. If there was a volume of unaccounted water then the processes that lead to this loss can be identified. Units for all variables are either in gigalitres (GL) or megalitres (ML).

## Farm Water Balance Framework

There are many farms in the focus valleys. Any surface water received by the farm (i.e. irrigation, on-farm storage and water harvested) is deemed as surface water input to the farm and surface water that is lost by the farm (surface runoff) is considered as surface water output. Substituting the surface water inputs and surface water outputs into the generic equation we obtain the following water balance equation for the farm scale:

$$\mathbf{P + DL + OFS + WH + GW = ET + E + DD + RO + \Delta S} \quad (5)$$

Where

P = Rainfall / Precipitation
DL = Deliveries
OFS = On Farm Storage
WH = Water Harvested
GW = Ground Water
ET = Evapotranspiration
E = Evaporation (from storage)
DD = Deep Drainage
RO = Runoff
$\Delta$S = Change in Soil Moisture
M/O E = Measurement or Operational Error

The equation above was simplified and put in the form

$$\mathbf{\Delta S = P + IW - ET - DD - RO} \quad (6)$$

Where

$\Delta$S = Change in soil moisture is the difference between the final and initial total amount of moisture(final minus initial) that is stored and/or retained in the soil in the root zone (directly available to crop) on the farm over a specified profile depth during the water year.

P = Rainfall is the total amount of water from rain that falls on the farms during the year.

IW = Irrigation water is the total amount of water that is used for irrigation on the farm during the year. It includes deliveries (the total amount of water delivered to the farm by the scheme and/or water pumped directly from the river); on farm storage (the total amount of water that is stored in on-farm storage at the beginning of the irrigation season); water harvested (the total amount of water harvested from rainfall directly to the crop during the irrigation season; ground water (the total amount of water pumped from the ground into the farm).

ET = Evapotranspiration also referred to as crop water use (CWU) is the total amount of water used by the crop on the farm during the year. It includes evaporation from the bare soil and transpiration via the plant (mm).

DD = Deep drainage is the total amount of water lost due to drainage from the farm and/or leaves through the soil on the farm during the year.

RO = Runoff is the total amount of water that run off from the farm as overland flows and irrigation discharge either to disperse over low-lying areas or be recycled during the year.

M/O E = Measurement of error is the estimate of amount of error that occurs due to measurement and can apply as both an input and an output.

Equation (6) can be used to calculate the change in soil moisture for the farm scale and for the assessment of water use efficiency. Units for the farm scale water balance variables can be either in megalitres (ML) or millimetres (mm).

It should be noted that because of the generic nature of the frameworks some individual components of the above equations may not be applicable for every application.

### *LINKAGES BETWEEN SCALES*

Once the water balance components were identified at each spatial scale, the linkages, or volumes of water that flow between the spatial scales become more evident. These linkages between spatial scales may include irrigation water diversions from a catchment scale to a scheme or recharge to a regional aquifer that in turn may be pumped for irrigation at farm scale. Figure B. 5 shows the linkages (linkages shown as thick black lines) between the spatial scales.

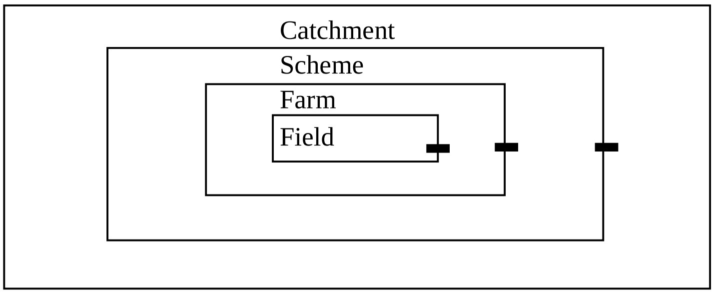


**Figure B. 5. Conceptual diagrams representing the irrigation cycle.**

The linkages can be explored in two ways. Firstly, sinks for water on single spatial scales may flow to other scales and be used, such as irrigation diversions or deep drainage. Secondly, water use can be partitioned between known physical processes such as evaporation and deep drainage. Here the assumption is that the unaccounted water is the source of water for processes such as deep drainage, surface runoff and evaporation. These can be partitioned to account for the water use. It can be seen from Figure B. 5 that the catchment is the highest spatial scale where water can be accounted. In this way all freshwater use takes place in a catchment (Molden et al 1999). It should noted that for the purpose of this project, the farm and field scales have been combined together for simplicity.

# APPENDIX C: DATA COLLECTION AND METHODOLOGY FOR INITIAL FRAMEWORK

## DATA COLLECTION

Data was determined by assessing the various components of the water balance frameworks that have been developed at each nested scale. The method consisted assessing the various incoming and outgoing water flux over the year. Data were collected from many sources that include but are not limited to state sources (DIPNR, NSW DPI), electronic sources, industry experts, irrigation scheme records, simulation models, integrated quantity and quality model (IQQM/DIPNR), SILO and other relevant research. Some data were collected in collaboration with NSW DPI staff in regional offices. As these staff uncovered regional data (for example, unpublished reports), this information was incorporated and utilised into the project. Some data were scant or not available, for example, crop water use, deep drainage, surface runoff are surprisingly difficult figures to obtain. In such cases, computer simulations were conducted to simulate water balance and generated such data (see Appendix D). It is important to note however that this project is not about collecting any new information but endeavours to value add to the existing data sets.

### Catchment Scale Data

Rainfall, dam releases, tributary inflows, diversions and end of system flows were collected for the Macquarie and Murrumbidgee catchments from various sources. Measured data were obtained mainly from Dept. of sustainable natural resource, Dept. of infrastructure planning and natural resources (DIPNR) and the State Water database. The sources of modelled data including various spreadsheets, the integrated quality and quantity model (IQQM) either from model input data already aggregated or from model predictions through simulation from the DIPNR database. The following is the detailed description of data collected at this scale:

- Rainfall

Catchment rainfall is the total amount of water from rain that falls on the surface of the catchment during the year. Catchment rainfall was calculated as the total surface area of the catchment multiplied by the average annual rainfall across the valley. Average annual rainfall across the Murrumbidgee and Macquarie catchments for each year from 1957 to present (Grouped GIS data for both catchments in ArcMap) were obtained from the Bureau of Meteorology (BoM) as shown in table 4.1. The average annual rainfall across the catchments was calculated by totalling the grid values across each basins polygon and dividing this total by the number of grids which fell within each polygon. Only grids whose centre point fell within the basin polygons were included in the calculation.

- Dam Releases

The total amount of water that is released by the dam into the catchments during the year. Measured dam releases were obtained from state water database (D Barnes pers comm) and the DLWC annual reports (McCormick and Bell 2000; Gardner and West 1999). The modelled IQQM data from 1890 to present were obtained from DIPNR. Data on Burrendong dam releases were collected for Macquarie catchment. It should be noted that Windamere dam is also a major regulatory structures in the Macquarie valley however no data was collected for this dam. This is because Windamere dam is situated at the top of the Cudgegong river and its water outflows are released into the river mainly to supplement Burrendong dam during dry years (EPA 1997). These flows were not considered as translucent flows and therefore were not utilised and/or added to the Burrundong dam releases. For Murrumbidgee catchment, data on the Burrinjuck and Blowering annual dam releases and spills were collected.

- Tributary Inflow

Tributary inflow includes all water that enters the river from the tributaries of the catchments during the year. For Macquarie catchment, modelled IQQM data for the total volume of gauged tributaries inflows (ML) of Macquarie river downstream of Burrendong dam for the period 1890 - present were collected from DIPNR. For Murrumbidgee cathment, modelled IQQM data for 1892 - present on the Marr Tumut, annual tributary inflows downstream of Burrinjuck and Blowering dams of the Murrumbidgee were obtained from DIPNR. No data are available for ungauged tributary inflows.

- Diversions

The total amount of water diverted from the river system to the schemes during the year (ML). IQQM modelled diversions from Macquarie river (1890 – present) and Murrumbidgee river (1892 – present) were obtained from DIPNR. Measured data on diversions were also obtained from Macquarie and Murrumbidgee Irrigation Profile (Hope 2001).

- End Of System Flows

The total amount of water that is uncommitted and/or environmental flows at the determined end point of the catchment during the year. The determined end point of the Macquarie catchment is at Carinda whereas that of the Murrumbidgee catchment is set at Balranald. Data on end of system flows at Carinda for years 1938 to 1986 were obtained in the form of graphs from the Dept. of water resources report (1991). The environmental end of system flows set at Carinda and Balranald for the years 1993 to 1998 were obtained from state water database (D Barnes) whereas those for years 1999 to 2000 were obtained from the relevant Department of Land and Water Conservation annual reports.

**Table C. 1. Mean annual rainfall of the Macquarie and Murrumbidgee catchments.**

| | **Macquarie (polygon 10)** | **Murrumbidgee (polygon 21)** |
|---|---|---|
| **Year** | **Mean (mm)** | **Mean (mm)** |
| 1957 | 383 | 295 |
| 1958 | 576 | 593 |
| 1959 | 539 | 644 |
| 1960 | 675 | 533 |
| 1961 | 593 | 558 |
| 1962 | 541 | 584 |
| 1963 | 622 | 689 |
| 1964 | 579 | 527 |
| 1965 | 409 | 307 |
| 1966 | 602 | 521 |
| 1967 | 265 | 341 |
| 1968 | 565 | 587 |
| 1969 | 691 | 727 |
| 1970 | 673 | 610 |
| 1971 | 581 | 628 |
| 1972 | 403 | 428 |
| 1973 | 809 | 901 |
| 1974 | 923 | 678 |
| 1975 | 634 | 528 |
| 1976 | 472 | 744 |
| 1977 | 396 | 482 |
| 1978 | 741 | 776 |
| 1979 | 413 | 406 |
| 1980 | 458 | 390 |
| 1981 | 592 | 586 |
| 1982 | 261 | 293 |
| 1983 | 691 | 703 |
| 1984 | 639 | 707 |
| 1985 | 552 | 522 |
| 1986 | 540 | 456 |
| 1987 | 462 | 561 |
| 1988 | 684 | 670 |
| 1989 | 686 | 633 |
| 1990 | 591 | 745 |
| 1991 | 501 | 476 |
| 1992 | 757 | 690 |
| 1993 | 642 | 690 |
| 1994 | 389 | 345 |
| 1995 | 664 | 583 |
| 1996 | 601 | 657 |

| | | |
|---|---|---|
| 1997 | 403 | 433 |
| 1998 | 542 | 774 |
| 1999 | 649 | 711 |
| 2000 | 592 | 761 |
| 2001 | 455 | 469 |
| 2002 | 353 | 340 |
| 2003 | 537 | 537 |

*Source: Bureau of Meteorology (BoM) grouped GIS data in ArcMap.*

### Scheme Scale Data

Scheme water balance data on rainfall, deliveries and diversions are collected. Some scheme irrigation volumes were obtained from relevant schemes publications and authorities. Others were obtained form scheme offices, delivery and billing data which is recorded on field sheets and from individual scheme representatives. However, data on this scale were limited. For this reason, data for period of 6 years (1995/95 – 2000/01) only have been collected for each of the respective schemes.

- Rainfall

Scheme rainfall is the total amount of water from rain that falls on the scheme channels during the year. Scheme rainfall was calculated as the total area of the scheme channels multiplied by the average annual rainfall across the valley (Table C. 1). Data on the total area of each irrigation scheme channels were obtained from irrigated farming within the Macquarie valley (Elliot 1995) and the irrigation profiles compiled by Hope (2003).

- Deliveries

Deliveries are the total amount of water that is delivered to the farm gate from the scheme during the year. Scheme deliveries were obtained from relevant schemes publications and authorities. For example, Narromine scheme deliveries were obtained from Narromine action plan, (NBIM 2001). Other data on irrigation deliveries were obtained from individual scheme representatives (Lyn Davies Pers Comm). Lynn is the secretary for the respective schemes.

- Diversions

The total amount of water diverted from the river system to the scheme during the year. Modelled IQQM data on diversions for the period 1890 - present were obtained from DIPNR. Measured diversion data were obtained from irrigation profiles (Hope 2001) and relevant schemes publications and authorities. For example water diversions into the CIA were obtained from the Coleambally Irrigation Cooperative Limited (CICL) annual reports.

### Farm Scale Data

Because of the nature of the data at the farm scale (i.e. crop water use, deep drainage, surface runoff etc), these data were sometimes scant or never collected. For this reason, modelled (theoretical) data were generated using the Wasim (Water simulation) model. Computer simulation modelling were undertaken to simulate the soil and water relationships in response to different management strategies and environmental scenarios. Data for farm scale from the modelling techniques conducted included the following:

- Rainfall

Rainfall is the total amount of water from rain that falls on the farms during the year. Total annual rainfall and gross rainfall data on each day were obtained from SILO. It should be noted that the Wasim model requires a time series of daily rainfall data as an input. It should also be noted that not all rainfall is useful. The useful portion of rainfall is the effective rainfall or utilizable rainfall. However, the term effective rainfall can be interpreted differently not only by professionals in different fields but also by different workers in the same field. In the modelling work undertaken for this project this effective (net) rainfall is loosely defined as that part not intercepted by the crop canopy and directly evaporated.

- Irrigation Water

The total amount of water used for irrigation on the farm during the year. It includes deliveries, on-farm storages, water harvested directly to the crop and groundwater. The irrigation was mainly determined by the model depending on the scheduling plan.

- Surface Runoff

Surface runoff is the total amount of water that runs off from the farm as a result of rain and irrigation discharges either to disperse over low-lying areas or be recycled during the year. In Wasim modelling, surface runoff is loosely defined as runoff due to the intensity of rainfall (infiltration excess) and runoff due to saturated soils.

- Deep Drainage

The total amount of water lost due to drainage from the farm and/or leaves through the soil on the farm during the year. In the modelling process, it was estimated as the flow to the water table below the drainage depth.

- Crop Water Use

The crop water use also referred to as crop evapotranspiration (ET) is the total amount of water used by the crop on the farm during the year. Wasim model required a time series of daily reference ET as an input. Reference ET was determined using the WaSimET utility provided for calculating it from daily climate data using the Penman-Monteith and the historical crop water use (HCWU) daily and monthly time step model that was developed by the Water Use Efficiency Advisory Unit. In Wasim, the actual crop ET is estimated as the actual crop transpiration, soil evaporation and evaporation of intercepted water from mulch cover.

- Soil Moisture Change

The difference between the final and initial total amount of moisture (final minus initial) is the moisture retained in the soil in the root zone (directly available to crop) on the farm over a specified profile depth during the year. The soil moisture change was calculated as the difference between the amount water inputs (irrigation plus rainfall additions) and water outputs (evapotranspiration, deep drainage and surface runoff).

Data obtained from Wasim model on each of the above water balance variable in mm were converted to ML by multiplying by the farm areas irrigated (mm to ML: Area irrigated (ha) $\times$ value of water balance variable (mm) $\times$ 0.01). Areas irrigated were obtained from profiles on irrigation compiled by Hope (2003). Other data utilised in this project included that from the NSW Dept. of primary industries (DPI) agronomist and irrigation officers and expert opinions and best guesses knowledge data. For example, data on crop yield (G. Giddings, Irrigation Officer and B. Swann, Irrigation Advisory Officer, NSW DPI, Dubbo, pers comm.), area of crop irrigated (Barma 2001, pers comm., and DLWC 1998), total area occupied by channels (relevant irrigation schemes authorities such as Narromine Irrigation Action Plan), catchment areas (Udai Pradhan 2004, Spatial Information Officer, NSW DPI, Orange, and ABS 1997). The total areas of the respective schemes were obtained from the report on irrigated farming within the Macquarie valley (Elliot 1995).

## APPENDIX D: THE USE OF COMPUTER MODELS TO SIMULATE FARM SCALE DATA

Computer models have been developed to describe the each of the factors that influence the movement of water in the soil. This section covers the computer model used in this project to generate data that were scarce or not available – specifically data such as the volume of water used on crop, runoff and deep drainage at the farm scale.

WaSim (Water Simulation) is the model that was used to generate the water balance data for different irrigated crops and soil at the farm scale. The WaSim model is a one-dimensional computer-based daily soil water balance model that aims to simulate the soil water storage and rates of input (infiltration) and output (evapotranspiration and drainage) of water in response to climate and irrigation. Figure D. 1 shows the Wasim graphical interface.

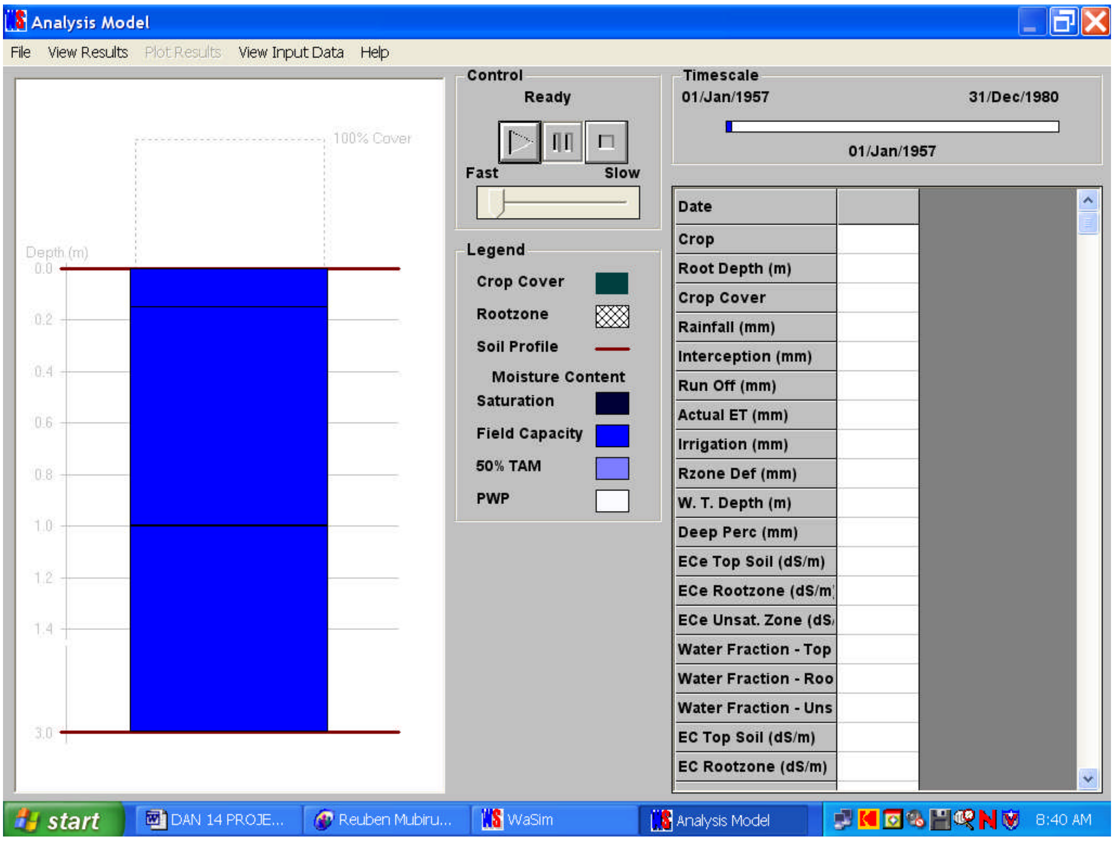


**Figure D. 1. Wasim graphical interface.**

Wasim is a very flexible model that can be used in many different ways. The model inputs include climate, soils, crops and irrigation data. Water is stored between the soil surface (upper boundary) and the impermeable layer (lower boundary) in five stores (compartments):

- Compartment 1: The surface layer (0 – 0.15m),
- Compartment 2: The active root zone (0.15m – root depth),
- Compartment 3: The unsaturated layer below the root zone (root depth – watertable),
- Compartment 4: The saturated layer above drain depth (watertable – drain depth),
- Compartment 5: The saturated layer below drain depth (drain depth –impermeable layer).

The boundary between compartments 2 and 3 will change as the roots grow. Before plant roots reach 0.15m, compartments 2 will have zero thickness. Similarly the boundary between compartments 3 and 4 will fluctuate with the watertable. Soil water moves from upper layers to layers below only when the soil water content of the layer exceeds field capacity but the rate of drainage is a function of the amount of the excess water. Upward capillary rise occurs from the water table to the root zone. The water balance results from Wasim can be displayed on a seasonal (crop season), monthly or annual basis.

Other tools that were used to store, analyse and manipulate data and output from the water balance included Excel and Access.

### WASIM MODELLING TECHNIQUES

Computer simulation is a modelling technique that is used to approximate the behaviour of a system on a computer, representing all the characteristics of the system largely by mathematical or algebraic expressions. It provides the response of the system for certain inputs so that a decision maker may examine various scenarios of an existing system without actually building it.

The modelling technique undertaken for this project was to run several simulations using the Wasim model with different scenarios (e.g. different irrigation schedules) for many different irrigated crops and different soil types in the Macquarie and Murrumbidgee valleys. The model requires a time series of daily reference ET and rainfall as climate input data. In addition, the crop and soil parameters and irrigation schedule need to be defined. These data were extracted from many sources and in varying computer software format (text files, spreadsheets, Access databases).

## Climate Data

The primary climate data required in the calculation of reference ET are air temperature, vapour pressure, solar radiation, wind speed and rainfall. These data for the respective irrigation schemes and areas within the valleys were extracted from different weather stations from the bureau of meteorology (BoM) and SILO patched point datasets. Daily time series data over the period from 1957 to present were extracted. This is because these data have been quality checked by the Bureau of Meteorology prior to interpolation. Prior to 1957, data were not extracted because these climate data are derived from long term daily means and are not computerised and reside on paper records in the Australian Archives.

- Narromine irrigation scheme

Data were extracted from Narromine airport station. The station has latitude of -32.22 decimal degrees and longitude of 148.23 decimal degrees at an elevation of 219.0 m.

- Buddah Lakes and Greenhide irrigation scheme

Data were extracted from Trangie post office station. The station has latitude of -32.03 decimal degrees and longitude of 147.98 decimal degrees at an elevation of 219.0 m.

- Marthaguy and Tenandra irrigation scheme

Data were extracted from Warren post office station. The station has latitude of -31.70 decimal degrees and longitude of 147.98 decimal degrees at an elevation of 198.0 m

- Nevertire irrigation scheme

Data were extracted from Nevertire hotel station. The station has latitude of -31.84 decimal degrees and longitude of 147.72 decimal degrees at an elevation of 198.0 m

- Trangie-Nevertire irrigation scheme

Data were extracted from Nevertire Beverley station. The station has latitude of -32.02 decimal degrees and longitude of 147.43 decimal degrees at an elevation of 219.0 m

- Murrumbidgee irrigation area (MIA)

Data were extracted from a range of weather station across the valley. These included Griffith CSIRO station that has latitude of -34.32 decimal degrees and longitude of 146.07 decimal degrees at an elevation of 126 m.

- For Coleambally irrigation area (CIA)

Data were extracted from the Coleambally Irrigation station. The station has latitude of -34.80 decimal degrees and longitude of 145.89 decimal degrees at an elevation of 126 m.

## Crop Data

Crop parameter files were created for irrigated crops that were identified as being grown in each of the valleys. Parameters included crop cover and root development and were mainly obtained from the Wasim technical manual guidance values, the NSW volumetric conversion database and "expert opinions and best guesses" relating to different crops (Garry Giddings, Irrigation Officer, NSW DPI, Dubbo, pers. comm. & Col Mullen, District Agronomist, NSWAG, Dubbo, pers. comm.). Crop parameters include:

- Crop cover development

The crop cover development includes data on parameters such as date of planting, emergence, 20% cover, full cover, maturity, harvest and maximum root date. Also data on percentage of maximum cover, mulch cover and crop coefficient at full cover were required.

- Crop Roots

This includes data such as the planting depth (m) and maximum root depth (m).

- Crop transpiration parameters

Crop transpiration parameters include data on the depletion fraction (P-fraction). The P-fraction is the average fraction of total available soil water (TAW) that can be depleted from the root zone before moisture stress (reduction in ET) occurs [0-1]. The P-fraction differs from crop to crop and normally varies from 0.3 (for high $ET_c$ rates > 8mm/d) to 0.7 (for low $ET_c$ rates < 3mm/d). A value of P = 0.5 is commonly used for many crops. A range of guidance values for P-fraction are were obtained from FAO publication 56 (Allen *et al.* 1998).

## Soil Data

Data on physical parameters of twelve different typical soil types and/or textures within the valleys were collected and used in the simulations. The soils simulated included clay, clay loam, loam, loamy sand, sandy clay, sandy clay loam, sandy loam, sandy silty, silt loam, silty clay and silty clay loam. Only single layered soils can be simulated in Wasim. Data on these soil textures (size of individual mineral particles that make up a soil) were calculated or obtained from either the Wasim technical manual guidance values or the soil texture triangle (http://wilkes1.wilkes.edu/~boram/soilwatr.htm), which provides a prediction of the hydraulic properties of different soils. Data on the following soil parameters were utilised:

- Field capacity as the percentage of water held in the soil at field capacity.

Field capacity is the maximum amount of water that a particular and/or well-drained soil can hold against gravitational forces or the amount of water remaining when downward drainage has markedly decreased.

- Soil saturation as the percentage of water held in the soil at saturation.

A condition in which all easily drained voids (pores) between soil particles are temporarily or permanently filled with water; significant saturation during the growing season is considered to be usually one week or more.

- Water retention

Soil particle size varies directly with air retention, and inversely with water retention. This means that, as the particle size decreases, so does the amount of air retained at the saturation point. It also means that, as the particle size decreases, the amount of water retained increases.

- Infiltration (intake) rate

The soil water infiltration (intake) rate is an important variable influencing soil water dynamics and runoff.

- Hydraulic conductivity which is a measure of the capability of a soil medium to transmit water (m/d).

- Permanent wilting point

Permanent wilting point as the percentage of water held in the soil at the water content at which a plant will permanently wilt.

- Depth of soil profile

If no water table simulation is to be undertaken (and consequently the depth to the impermeable layer is not specified) a depth of soil profile needs to be entered.

- Curve Number

The Curve Number is used in the calculation of surface run-off, and is adjusted during the simulation to take into account the relative saturation of the top layer of soil. The value entered into the form is assumed to be the Curve Number for average antecedent moisture conditions.

- Drainage Coefficient

Used in the calculation of drainage when the volume water fraction is between Field Capacity and Saturation.

### Irrigation Data

In Wasim, two procedures are available for defining irrigation plans or schedules. These are (1) Rule based irrigation scheduling where rules, such as irrigate at 50mm soil water deficit and refill to field capacity, determine the timing of irrigation and the amount of water to be applied, and (2) Calendar irrigation scheduling were fixed dates (e.g. apply 50mm 10 days after planting) are specified to simulate irrigation. If no irrigation is required then the no irrigation option can be selected.

The rule based irrigation plans developed to determine the timing of irrigation and the amount of water to be applied on individual crops for this project included the following:

- Irrigation plan 1

Irrigating at fixed deficit of 50 mm, and at fixed amount of 100 mm (Fixed deficit (50 mm), Fixed amount (100 mm))

- Irrigation plan 2

Irrigating at fixed deficit of 50 mm, and then return to 0 mm deficit (Fixed deficit (50 mm), Return to 0 mm deficit)

- Irrigation plan 3

Irrigating at fixed deficit of 50 mm, and then return to 20% total available moisture (TAM) depletion (Fixed deficit (50 mm), Return to 20% TAM depletion)

- Irrigation plan 4

Irrigating at fixed depletion of 50% TAM, and at fixed amount of 100mm (Fixed depletion (50%), Fixed amount (100mm))

- Irrigation plan 5

Irrigating at fixed depletion of 50% TAM, and then return to 0 mm deficit (Fixed depletion (50%), Return to 0 mm deficit)

- Irrigation plan 6

Irrigating at fixed depletion of 50% TAM, and then return to 0% TAM depletion (Fixed depletion (50%), Return to 0% TAM depletion)

- Irrigation plan 7

Irrigating at a fixed interval of 10 days, and at fixed amount of 30mm (Fixed interval (10 days), Fixed amount (30mm))

- Irrigation plan 8

Irrigating at a fixed interval of 10 days, and then return to 0mm deficit (Fixed interval (10 days), Fixed deficit (0mm))

- Irrigation plan 9

Irrigating at a fixed interval of 10 days, and then return to 0% TAM depletion (Fixed interval (10 days), Return to 0% TAM depletion)

- Irrigation plan 10

No irrigation at all.

The calendar based irrigation plans and dates specified to simulate irrigation by a fixed calendar on individual crops for this project included the following:

- Irrigation plan 11

Apply 173.4, 119.0, 90.2, 53.5 and 65.7mm after 4, 96, 118, 130, 150 and 269 days of planting respectively.

- Irrigation plan 12

Apply 78.5, 77.7, 39.8, 35.4, 26.6, 43.2, 21.2, 29.0 and 26.6mm after 4, 91, 106, 119, 127, 135, 144, 155, 164 and 260 days of planting respectively.

This option can also be used to simulate the impact of an actual irrigation schedule. The scheduling criteria include the ability to suspend irrigation due to rainfall, or constrain the schedule due to limiting system capacity. The model allows up to 12 combinations of frequencies and amount of irrigation between selected dates and the start date for each irrigation scheduling period was assumed to be the date at which the previous period was finished. In the case of the first period the start date is assumed to be the crop planting date.

It should be noted however that in simulation it is not the complexity of the model used that is important, but that the model is able to predict the actual conditions with a certain amount of accuracy. A single model validation and data analyses was undertaken. This involved a comparison between field-measured data and outputs from the model as shown in the next section.

### Validation of Wasim Model

A cotton crop was selected to provide some validation of the Wasim modelling results based on the work of Willis, Black and Mayer (1997). The cotton crop grown was chosen because of the availability of data (Willis et al 1997) and the fact that it is the dominant irrigated crop in Macquarie valley. The crop is grown on two soil types, that is, the red brown soils that belong to the Wilga soil profile – calcic phase (McKenzie 1992) and the cracking clay soils of the Mullah soil profile (Soil survey staff 1975) in the lower Macquarie valley. These are contrasting soils (Joshua pers. comm.) and Wilga soils have been reported to have higher permeability than the Mullah soils (McKenzie 1992).

Several soil, crop and irrigation parameters were “trialled” until there was a reasonable scenario that most correctly matched that reported in the work of Willis, Black and Mayer (1997). The modelled and experimental water balance data were compared. The irrigation regimes included two irrigation calendar based plans that were scheduled to match the actual irrigation regime used by the researcher (Willis et al 1997) in the experiment in the lower Macquarie valley. These included irrigation plan 11 for Mullah soil profile and irrigation plan 12 for Wilga soil profile. Figure D. 2 and Figure D. 3 show the comparison of the modelled and experimental water balance data for the cotton crop whereas the overall water balance results are presented in Table D. 1.

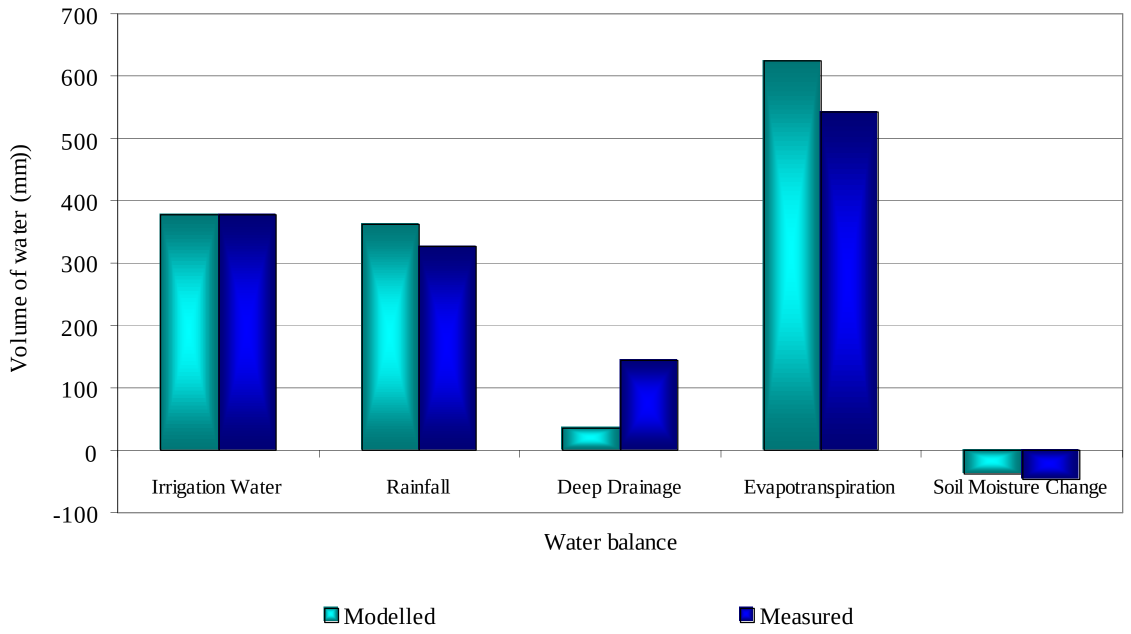


**Figure D. 2. Comparison between modelled and experimental (Willis et al 1997) cotton crop water balance for Wilga soil profile.**

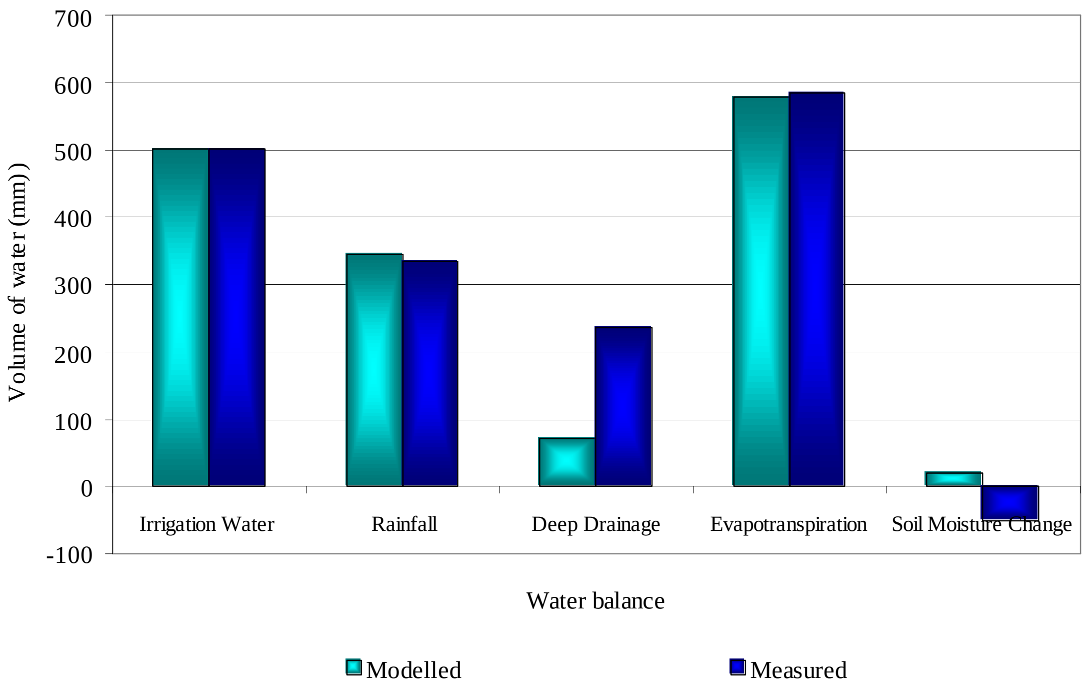


**Figure D. 3. Comparison between modelled and experimental (Willis et al 1997) cotton crop water balance for Mullah soil profile..**

**Table D. 1. Comparison between modelled (Wasim) and experimental (Willis et al 1997) cotton crop water balance data.**

| Parameter | Wilga Soil Profile 1992/1993 | | Mullah Soil Profile 1992/1993 | |
|---|---|---|---|---|
| | Experimental | Modelled | Experimental | Modelled |
| Total $ET_c$ (mm) | 542.4 | 624.3 | 584.8 | 578.8 |
| Total Rainfall (mm) | 327.5 | 361.3 | 335.1 | 345.1 |
| Total Irrigation (mm) | 378 | 378 | 501.8 | 501.8 |
| Total deep drainage (mm) | 145.2 | 35.0 | 236.1 | 71.6 |
| Soil Water Change (mm) | -47.5 | -38.0 | -51.1 | 20.4 |
| Total Surface Runoff (mm) | | 118.0 | | 176.1 |
| Number of irrigations | 9 | 9 | 5 | 5 |

Note: Surface runoff was not measured

The results show that there is a relatively greater difference between the modelled and experimental deep drainage for both Wilga and Mullah soil profiles. The difference between the modelled and measured deep drainage can be probably explained by the fact that the researchers (Willis et al 1997) who undertook the water balance experiment in the lower Macquarie valley obtained their deep drainage values shown in these figures using the water balance techniques. They described deep drainage as the difference between the measured amounts of irrigation plus rainfall that have infiltrated the soil profile and evapotranspiration plus changes in stored soil water content, DD = (IW+0.8P) – (ET+SMC) where it was assumed that 80% of rainfall infiltrated the soil profile in a furrow irrigated cotton field. This factor (0.8) is not used to convert the Wasim modelled rainfall figure. Wasim deep drainage predictions are based on the flow from the water balance to the drains as a function of mid-drain water table height (after Youngs et al 1987). However, the researchers also estimated deep drainage only for Mullah (G) soils using the Darcian flux calculation and it was found that the estimated deep drainage is 67 mm. This figure is in good agreement with the Wasim modelled deep drainage of 71 mm for Mullah (G) soils (Table D. 2).

**Table D. 2. Quantities of deep percolation and leaching fractions estimated for two soils using three techniques. The quantity that has infiltrated the soil profile (I + 0.8R) is 758 mm and 630 mm on the Mullah (G) and Wilga (C) soils respectively.**

| Method | Soil | Deep Drainage (mm) | Standard Error (mm) | Leaching Fraction (%) |
|---|---|---|---|---|
| Water Balance | Mullah (G)<br>Wilga (C) | 236<br>145 | n/a<br>n/a | 31<br>23 |
| Mass Balance | Mullah (G)<br>Wilga (C) | 214<br>104 | 13<br>2 | 28<br>17 |
| Darcian Flux Calculation | Mullah (G) | 67 | 53 | 8 |

*Source: Estimates of deep percolation beneath cotton in the Macquarie valley (Willis et al 1997)*

In addition, it can be seen that there is also a noticeable difference between the modelled and measured soil moisture change value especially with the Mullah soil profile. The barrier to the validity of soil moisture change results is that in practice the researchers did not measure the surface runoff. This would be expected to have some effect on the soil moisture change figure. Even a slight change in the surface runoff values can affect the soil moisture change considerably.

The result of other water balance components displayed acceptable deviation between modelled and measured data. Interrogation of the data for the 1992/1993 season indicates that the overall modelled water balance data were within +/- 10% of the measured water balance data for almost all components. It can thus be concluded that the water simulation model (Wasim) is able to simulate fairly accurately the water balance variables.

Accordingly, Wasim model has been used to generate water balance data on many different crops grown on many different soil types with different scenarios (e.g. different irrigation schedules) in the Macquarie and Murrumbidgee valleys. A total of eight different groups of simulations were conducted using Wasim with different scenarios (e.g. different irrigation schedules) for fifteen different irrigated crops and twelve different soil types in the Macquarie and Murrumbidgee catchement. Series of simulations were conducted for different irrigated crops on different soil types within the respective irrigation schemes based on the reports from the surveys conducted on the Murrumbidgee and Macquarie catchment irrigation profiles (Hope 2002; 2003) and irrigated farming within the Macquarie valley (Elliot 1995).

- Narromine Irrigation Scheme

Irrigated cotton and Lucerne crops grown on clay, clay loam, loam, loamy sand, sandy clay, sandy clay loam, sandy loam, sandy silty, silt loam, silty clay and silty clay loam soils using irrigation plans (1,2,3,4,5,6,7,8,9,10, 11 and 12).

- Trangie-Nevertire Irrigation Scheme

Irrigated canola, soybeans and sunflower crops grown on clay, clay loam and sandy loam soils using irrigation plans (1, 4 and 8).

- Tenandra and Marthaguy Irrigation Schemes

Irrigated barley, perennial pasture (rotational dairy) and citrus crops grown on clay, clay loam, and sandy loam soils using irrigation plans (1, 2 and 3).

- Buddah Lakes and Greenhide Irrigation Schemes

Irrigated winter wheat and annual pasture crops grown on clay, clay loam, and sandy loam soils using irrigation plans (6 and 9).

- Nevertire Irrigation Scheme

Irrigated potatoes, grapes (wine) and tomatoes crops grown on clay, clay loam, and sandy loam soils using irrigation plans (5, 6 and 7).

- Murrumbidgee Irrigation Areas (MIA)

Irrigated barley, canola, carrots, citrus, fababean, garlic, maize, olives, potatoes, pumpkin, rice, soybeans, sunflower, tomatoes and wheat crops grown on clay, clay loam, and sandy loam soils using irrigation plans (6 and 9).

- Coleambally Irrigation Areas (CIA)

Irrigated Orchards (chill) and fababean crops grown on clay, clay loam, and sandy loam soils using irrigation plans (5, 6 and 7).

## Appendix E: Bayesian Networks – Initial Methodology

The emphasis in this project has been placed on determining whole of system water use efficiencies WOS WUE for the Macquarie and Murrumbidgee river valleys. This whole of system perspective is required to provide a valid assessment of the potential water savings for each scale. However, measuring whole of system water use efficiency is conceptually and logistically complicated. There are two main reasons for this complexity. Firstly, understanding the stochastic nature of the long-term water balances on a whole of system level, coupled with the uncertainties makes the seemingly simple task of constructing a water balance, very complex. Secondly, the calculation of WOS WUE involves a large quantity of information and data. Moreover, most of the decisions and management implementation plans that need to be made at a whole of system level have more than one consequence and it becomes difficult to keep track of the consequences.

The Bayesian networks (BN) were employed as a tool for this project in an attempt to handle this complexity. In essence, Bayesian Networks are decision support system tools (DSS) that can be used to help structure decision processes and support analysis of the consequences of possible decision choices by making information and data easily accessible and allowing “what if” analyses. The Bayesian networks provide a method to represent relationships between variables even if relationships involve uncertainty, unpredictability or imprecision based on conditional (Bayesian) probability theory. Bayesian networks are picture-based (graphical) explanations that are simple to understand and may be adapted quickly. Links between variables can be established deterministically or probabilistically by observation or expert opinion. Netica’s representation of a Bayesian networks is through three elements:

- A set of nodes

These represent management system variables. There are 3 types of nodes; nature, utility and decision nodes. The nature nodes sometimes called “deterministic nodes” or “chance nodes” describe the possible state of the variable and the likelihood of each state in probability terms and can be qualitative or quantitative (discrete or continuous) measures. The utility nodes describe the desirability of the consequences of a set of outcomes and represent variables that the decision maker is trying to optimise. The decision nodes represent variables that the decision maker can control (Norsys Software Corp. 1997).

- A set of links

These represent relationships between the nodes. Links have direction from cause to effect. If there is a link from node A to node B, B is described as a child of A, and A as a parent of B.

- A set of probabilities

One probability for each node specifying the belief that a node will be in a particular state given the state of those nodes that affect it directly (its parents). These are called conditional probability tables (CPTs) and can be used to express how the relationships between the nodes operate. Conditional probability is the probability of an event occurring given that another event also occurs. It is expressed as P(A/B), which can be read as “Probability of Event A on condition that Event B occurs.

$$P(A/B) = P(A \text{ and } B)/P(B)$$

*Where*
P(B) is the probability of event B
P(A and B) is the joint probability of A and B

The Netica graphical component of a Bayesian Network diagram consists of nodes and links and does not include the conditional probability tables. The Bayesian network diagram is more formally called a directed acyclic graph (DAG) and the logic underlying it is that it is represented by the network structure (how the nodes are linked together), names of the nodes and names of the state of the nodes. The general structure of the Bayesian network consists of mainly six categories of variables, which are:

(1) Management objectives: These are things that need to be improved or prevented from worsening through management of water resources such as crop water use, unaccounted for water (potential water to be saved), irrigation scheduling etc.

(2) Management interventions: The things that need to be implemented in order to achieve the management objectives such as water recycling, line channels, dam construction, adopt sustainable agriculture etc.

(3) Intermediate factors: These are factors which link objectives and interventions such as “yield” linking “support and train growers” and “income”.

(4) Controlling factors**:** These are factors that cannot be changed by intervening at the scale you are considering but control the environmental system in some way. For example at a catchment scale, these can be rainfall, government policy etc.

(5) Implementation factors: These are factors which directly affect whether the intervention can be successfully implemented both immediately and in the future (depending on whether the intervention is implemented as a one-off or over a longer period). For example “funding” for “on-ground sustainable agricultural projects”, “community support” for “regulation of ground water extraction” etc.

(6) Additional impacts: These are factors which are changed as a result of interventions that do not affect anything else in the environmental system. Dependent on the system you are considering. For example, in water resources management if an intervention “increasing forest cover” is implemented it may lead to decreasing river flow as well as an increase in biodiversity. The increase in bird population is unlikely to affect the water resources in any way and so it may be classified as an additional impact.

The computer software “Netica” was used to construct the Bayesian Networks for this project based on the water balances identified at three nested interlinked spatial scales (i.e. catchment, scheme and farm). Water balance nodes and management decisions made by the irrigators (i.e. what type and area of crop to plant, area to irrigate, scheduling, irrigation system etc) were introduced to represent the process considered in the assessment of water use efficiency at the three nested spatial scales. The assessment criteria forming a basis for the decisions were considered to be the water use efficiencies and indices that were identified at each scale. These include but are not limited to farm, scheme storage and conveyance efficiencies and overall project efficiencies.

The variables (nodes) introduced have been named using actual names and a number of acronyms and their meaning and/or explanations are given (also see the description section of the network diagram). Mainly one meaning is assigned to each node and/or acronym. In the case where more than one meaning is possible the correct meaning is evident from the text in which it is used. **Error! Reference source not found.** shows the general structure of the WOS WUE master Bayesian network diagrams that have been developed for the NSW river valleys.

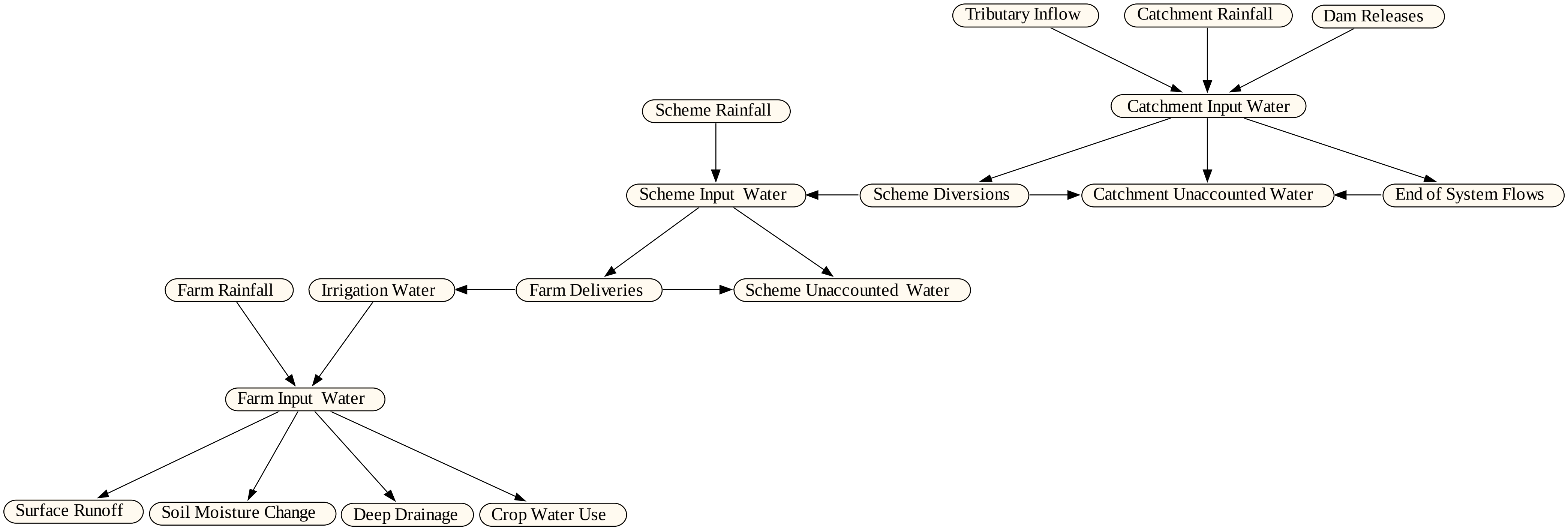


**Figure E. 1. Master Bayesian network representing whole of system water balance variables (nodes) for NSW River Valleys.**

The following section gives a brief explanation of all the variables (nodes) shown in **Error! Reference source not found.** and the description of the recognised relationships that exists between them.

- Farm Rainfall (fp): The total amount of water from rain that falls on the farms during the year. This is effective rainfall, hence useful or utilizable rainfall.

  Parent node of:
  - Farm Input Water

  Child node of:
  Nil

- Irrigation Water (iw): The total amount of water that is used for irrigation on the farm during the year. It includes deliveries, on-farm storages, water harvested directly to the crop and groundwater.

  Parent node of:
  - Farm Input Water

  Child node of:
  - Deliveries

- Farm Input Water (fiw): The total amount of water inputs and/or inflows (rainfall, irrigation water) that is available to the farm during the water year.
  Parent node of:
  - Surface Runoff
  - Soil Moisture Change
  - Deep Drainage
  - Crop Water Use

  Child node of:
  - Rainfall
  - Irrigation Water

- Surface Runoff (sr): The total amount of water that runs off from the farm as a result of rain and irrigation discharges either to disperse over low-lying areas or be recycled during the year.

  Parent node of:
  Nil

  Child node of:
  - Farm Input Water

- Soil Moisture Change (smc): The difference between the final and initial total amount of moisture (final minus initial) that is stored and/or retained in the soil in the root zone (directly available to crop) on the farm over a specified profile depth during the year.
  Parent node of:
  Nil

  Child node of:
  - Farm Input Water

- Deep Drainage (dd): The total amount of water lost due to drainage from the farm and/or leaves through the soil on the farm during the year.

  Parent node of:
  Nil

  Child node of:
  - Farm Input Water
- Crop Water Use also referred to as Evapotranspiration (cwu): The total amount of water used by the crop on the farm during the year. It includes evaporation from the bare soil and transpiration via the plant. Many factors affect crop water use, these include climate, soil moisture, crop type, crop location, rooting depth of a crop etc.


 

Parent node of:
Nil

Child node of:
- Farm Input Water

- Deliveries (dl): The total amount of water that is delivered to the farm gate from the scheme during the year. It includes on-scheme storages.

  Parent node of:
  - Irrigation Water
  - Scheme Unaccounted for Water

  Child node of:
  - Scheme Input Water

- Scheme Rainfall (sp): The total amount of water from rain that falls on the surface of scheme during the year.

  Parent node of:
  - Scheme Input Water

  Child node of:
  Nil

- Scheme Input Water (siw): The total amount of water inputs and/or inflows (rainfall, diversion, ground Water etc) that entered into the scheme during the year.

  Parent node of:
  - Deliveries
  - Scheme Unaccounted for Water

  Child node of:
  - Diversions
  - Scheme Rainfall

- Diversions (dv): The total amount of water diverted from the river system to the schemes during the year.

  Parent node of:
  - Scheme Input Water
  - Scheme Unaccounted for Water

  Child node of:
  - Catchment Input Water

- Scheme Unaccounted for Water (suw): The potential water that could be saved at scheme level, is the difference between the volume of water input (rainfall additions plus the volume of water diverted from the river system) and the volume of water delivered to the farms. SUW may be partitioned between evaporation, deep drainage, illegal extraction (if applicable), end of system (if applicable), ground water, soil moisture change, surface runoff and crop evapotranspiration across the region.

  Parent node of:
  Nil

  Child node of:
  - Scheme Input Water
  - Deliveries

- Tributary Inflow (ti): The total amount of water that enters the catchment from tributaries during the year.

  Parent node of:
  - Catchment Input Water

- Scheme Unaccounted for Water

Child node of:
Nil

- Catchment Rainfall (cp): The total amount of water from rain that falls on the surface of the catchment during the year.

  Parent node of:
  - Catchment Input Water

  Child node of:
  Nil

- Dam Releases (dr): The total amount of water released by the dam into the catchment during the year.

  Parent node of:
  - Catchment Input Water

  Child node of:
  Nil

- Catchment Input Water (ciw): The total amount of water inputs and/or inflows (dam releases, rainfall, tributary inflow, surface runoff) that entered the catchment during the year.

  Parent node of:
  - Catchment Rainfall
  - Dam Releases
  - Tributary Inflow

  Child node of:
  - Diversions
  - End Of System Flows
  - Catchment Unaccounted for Water

- End of system flows (eos): The total amount of water that is uncommitted and/or environmental flows at the determined end point of the catchment during the year.

  Parent node of:
  - Catchment Unaccounted for Water

  Child node of:
  - Catchment Input Water

- Catchment Unaccounted for Water (cuw): The potential water that could be saved at catchment scale is the difference between the sum of the volume of input water and the sum of the quantified water outputs (volume of water diverted for irrigation and the end of system flows). CUW may be partitioned between evapotranspiration, deep drainage, ground water, surface runoff and illegal extractions.

  Parent node of:
  Nil

  Child node of:
  - Catchment Input Water
  - Diversions
  - End Of System flows

The explanations of variables (nodes) and the descriptions of the recognised relationships that exist between them apply to all other networks that have been developed for the initial methodology for assess WUE at a WOS scale.

Other variables (management objectives and interventions) were introduced to capture the idea of determining whole of system water use efficiency (WOS WUE) for the NSW valleys as will be shown later. The Bayesian networks that have been developed for this project are held on the computer, in the form of an accessible decision support system and interface with the intention to providing a method to support and promote whole of system water use efficiency decision making.

Data were analysed in a way that accounts for their spatial and temporal distributions before being fed into Netica so that the results are presented in a manner that will provide the greatest level of understanding and acceptance across various sectors (e.g. researchers, growers, policy makers etc).

Bayesian Networks provide the mechanism to draw together quantitative (output from external models, river diversions, groundwater levels, research data etc) and qualitative data (subjective assessments where quantitative data are unavailable) from all available sources. The results of the BN will be useful to policy formulators, industry group, future researchers, other agencies or anyone else involved and/or working with the management of integrated natural (water) resources. It is also intended to help address the growing promotion problems in the current natural (water) management practices. The computerised DSS and/or interface is an important project output that is transferable to other catchments in Australia. It should be remembered however that this report was not about generating new information but endeavours to value add to the existing data sets. The following section discusses the results of the Bayesian networks.

## RESULTS OF THE BAYESIAN NETWORKS STRUCTURE

This section discusses the results of Bayesian networks analyses undertaken for this project to assess whole of system water use efficiency. Several analyses were carried out on the networks for different scenarios to investigate (1) the influence of the key management interventions on project objectives and (2) the sensitivity of the project objectives (i.e. water use efficiencies, unaccounted for water, etc) to management interventions and/or decisions.

The analyses were conducted on Bayesian networks that have been compiled based on data that was collected and modelled for this project. There are some important implications and assumptions that have been made with reference to data collected and calculated for each scale. The networks mainly incorporated files that contained data on water balance components and some other key management decision variables for different irrigated crops in the Macquarie and Murrumbidgee valleys.

It is important to note that throughout this section, the term "management intervention" is used to represent things that need to be implemented in order to achieve the project objectives whereas "project objective" represents things that the project wish to affect through management of water resources. These include things that need to be improved or prevented from worsening.

### WATER BALANCE COMPONENTS

#### Catchment Scale

Table E. 1 shows the Macquarie catchment water balance components and calculated unaccounted for water (CUW) over the study period of 1967 to 2000 whereas Table E. 2 show those of the Murrumbidgee catchment for the period 1993 to 2000. The CUW is the water or flow that is unknown and not accounted for in the water balance at this scale. The CUW was calculated by the difference between the sum of the volume of input water and the sum of the quantified water outputs (volume of water diverted for irrigation and end of system flows).

**Table E. 1. Macquarie catchment water balance (GL).**

| | Water Inputs | | | | Water Outputs | |
|---|---|---|---|---|---|---|
| Year | Dam Releases | Tributaries Inflow | Rainfall | Total Input Water | End Of System | Unaccounted for Water |
| 1967 | 725.68 | 47.55 | 6,780.07 | 7,553.30 | 27.03 | 7,526.28 |
| 1968 | 454.48 | 157.78 | 14,472.88 | 15,085.14 | 21.62 | 15,063.52 |
| 1969 | 1,099.40 | 403.28 | 17,715.83 | 19,218.51 | 135.14 | 19,083.38 |
| 1970 | 1,104.21 | 667.22 | 17,244.22 | 19,015.65 | 67.57 | 18,948.08 |
| 1971 | 1,335.56 | 182.96 | 14,877.77 | 16,396.29 | 270.27 | 16,126.02 |
| 1972 | 1,090.31 | 263.25 | 10,316.54 | 11,670.10 | 94.59 | 11,575.50 |
| 1973 | 4,010.66 | 783.11 | 20,729.79 | 25,523.56 | 527.03 | 24,996.53 |
| 1974 | 1,868.34 | 270.59 | 23,650.11 | 25,789.04 | 621.62 | 25,167.41 |
| 1975 | 864.19 | 310.22 | 16,240.83 | 17,415.24 | 148.65 | 17,266.59 |
| 1976 | 1,430.12 | 251.62 | 12,087.69 | 13,769.43 | 324.32 | 13,445.10 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1977 | 714.73 | 193.82 | 10,139.96 | 11,048.51 | 162.16 | 10,886.35 |
| 1978 | 1,577.31 | 382.35 | 18,973.13 | 20,932.79 | 364.86 | 20,567.92 |
| 1979 | 747.98 | 58.08 | 10,568.68 | 11,374.74 | 121.62 | 11,253.12 |
| 1980 | 208.93 | 31.78 | 11,724.90 | 11,965.61 | 67.57 | 11,898.04 |
| 1981 | 764.81 | 184.34 | 15,154.80 | 16,103.95 | 54.05 | 16,049.89 |
| 1982 | 250.23 | 83.82 | 6,691.97 | 7,026.02 | 40.54 | 6,985.47 |
| 1983 | 509.36 | 278.17 | 17,700.27 | 18,487.80 | 54.05 | 18,433.74 |
| 1984 | 1,416.94 | 237.82 | 16,365.99 | 18,020.75 | 135.14 | 17,885.61 |
| 1985 | 639.76 | 98.06 | 14,139.13 | 14,876.95 | 54.05 | 14,822.90 |
| 1986 | 1,122.17 | 122.26 | 13,834.92 | 15,079.35 | 75.68 | 15,003.67 |
| 1987 | 852.66 | 89.2 | 11,831.53 | 12,773.39 | 0 | 12,773.39 |
| 1988 | 1,109.22 | 349.26 | 17,516.19 | 18,974.67 | 0 | 18,974.68 |
| 1989 | 1,820.13 | 641.95 | 17,584.93 | 20,047.01 | 0 | 20,047.02 |
| 1990 | 3,328.96 | 683.31 | 15,152.57 | 19,164.84 | 0 | 19,164.84 |
| 1991 | 770.89 | 268.53 | 12,838.68 | 13,878.10 | 0 | 13,878.10 |
| 1992 | 593.69 | 151.08 | 19,402.74 | 20,147.51 | 0 | 20,147.51 |
| 1993 | 763.32 | 252.74 | 16,437.37 | 17,453.43 | 93 | 17,360.44 |
| 1994 | 322.32 | 63.33 | 9,957.75 | 10,343.40 | 16 | 10,327.39 |
| 1995 | 252.68 | 39.02 | 17,019.31 | 17,311.01 | 82 | 17,229.01 |
| 1996 | 927.97 | 242.23 | 15,395.14 | 16,565.34 | 41 | 16,524.33 |
| 1997 | 376.18 | 72.72 | 10,336.62 | 10,785.52 | 5 | 10,780.52 |
| 1998 | 1,903.68 | 843.4 | 13,880.60 | 16,627.68 | 15.4 | 16,612.28 |
| 1999 | 1,225.48 | 319.32 | 16,626.30 | 18,171.10 | 350 | 17,821.10 |
| 2000 | 1,708.60 | 398.58 | 15,173.72 | 17,280.90 | 619 | 16,661.90 |
| Average | 1,114.44 | 277.14 | 14,663.62 | 16,055.20 | 134.97 | 15,920.23 |
| Median | 896.08 | 246.93 | 15,153.69 | 16,596.51 | 67.57 | 16,568.31 |

**Table E. 2. Murrumbidgee catchment water balance (GL).**

| | Water Inputs | | | | Water Outputs | |
|---|---|---|---|---|---|---|
| Year | Dam Releases | Tributaries Inflow | Rainfall | Total Input Water | End Of System | Unaccounted for Water |
| 1993 | 3,709.00 | 213.26 | 44,276.50 | 48,198.76 | 2,270.00 | 45,928.76 |
| 1994 | 2,816.00 | 817.18 | 22,115.48 | 25,748.66 | 209.00 | 25,539.66 |
| 1995 | 2,451.00 | 184.81 | 37,386 | 40,021.81 | 783.00 | 39,238.81 |
| 1996 | 3,591.00 | 170.58 | 42,144.64 | 45,906.22 | 1,078.00 | 44,828.22 |
| 1997 | 3,081.00 | 572.73 | 27,773.08 | 31,426.81 | 259.00 | 31,167.81 |
| 1998 | 2,483.00 | 622 | 49,651.40 | 52,756.40 | 648.00 | 52,108.40 |
| 1999 | 1,909.00 | 520 | 45,576.52 | 48,005.52 | 628.00 | 47,377.52 |
| 2000 | 2,659.00 | 1,569.00 | 48,768.45 | 52,996.45 | 1,467.00 | 51,529.45 |
| Average | 2,837.38 | 583.7 | 39,711.51 | 43,132.58 | 917.75 | 42,214.83 |
| Median | 2,737.50 | 546.37 | 43,210.57 | 46,955.87 | 715.50 | 45,378.49 |

The volume of unaccounted for water is the potential water savings that could be made at each scale. It can be seen from Table E. 1 that the median volume of unaccounted for water for Macquarie catchment over the study period of 33 years (1967 – 2000) is 16,568.31 GL or 99.8% of the median volume of total input water. The median end of system flow is about 134.97 GL/year or 33% of the median natural end of system flow for the Macquarie (Carinda) of 410 GL/year (MDBC 1995). Table E. 2 shows that the median volume of unaccounted for water for Murrumbidgee catchment scale over the study period of five years (1995 – 2000) is 45,378.49 GL or 96% of the median volume of total inflow (water input). The median end of system flow is about 715.50 GL ML.

Water may be lost at the catchment scale to evaporation directly to the atmosphere and non target crop through evapotransipiration, deep drainage, ground water and illegal extractions. This unaccounted water may also leave the spatial scale and may be recaptured at another level.

### Scheme Scale

Table E. 3 and Table E. 10 the water balance data over the period of 6 years (1995 to 2000) for Narromine, Tenandra, Buddah Lakes and Greenhide irrigation schemes and irrigated cotton farms within each these respective schemes of the Macquarie valley. These tables show that a significant amount of water is being lost at scheme scale. The scheme's unaccounted for water (SUW) was calculated as the difference between the volume of water input (rainfall additions plus the volume of water diverted from the river system) and the volume of water delivered to the farms. This volume of unaccounted for water is mainly attributed to evaporation, deep drainage, illegal extraction (if applicable), ground water (if applicable) and measurement error.

**Table E. 3. Water balance components for Narromine irrigation scheme (GL).**

| | Water Inputs | | | Water Outputs | |
|---|---|---|---|---|---|
| Year | Diversions | Rainfall | Total Input Water | Farm Deliveries | Unaccounted for Water |
| 1995/96 | 17.10 | 1.16 | 18.26 | 10.61 | 7.64 |
| 1996/97 | 35.09 | 1.05 | 36.14 | 28.09 | 8.05 |
| 1997/98 | 24.05 | 0.71 | 24.75 | 19.85 | 4.90 |
| 1998/99 | 33.15 | 0.95 | 34.09 | 28.15 | 5.94 |
| 1999/00 | 43.07 | 1.14 | 44.21 | 36.90 | 7.31 |
| 2000/01 | 40.12 | 1.04 | 41.16 | 33.73 | 7.43 |
| Average | 32.10 | 1.01 | 33.10 | 26.22 | 6.88 |
| Median | 34.12 | 1.04 | 35.12 | 28.12 | 7.37 |

**Table E. 4. Water balance components for irrigated cotton crop farms within Narromine irrigation scheme (GL).**

| | Water Inputs | | | Water Outputs | | | |
|---|---|---|---|---|---|---|---|
| Year | Rainfall | Irrigation Water | Total Input Water | Surface Runoff | Deep Drainage | Crop Water Use | Soil Moisture Change |
| 1995/96 | 5.79 | 7.58 | 13.38 | 2.43 | 0.13 | 10.18 | 0.64 |
| 1996/97 | 17.80 | 15.79 | 33.59 | 6.41 | 0.85 | 27.92 | -1.59 |
| 1997/98 | 13.29 | 27.86 | 41.14 | 3.94 | 0.54 | 35.99 | 0.67 |
| 1998/99 | 23.51 | 26.62 | 50.12 | 7.94 | 0.82 | 38.71 | 2.65 |
| 1999/00 | 24.28 | 24.14 | 48.42 | 7.69 | 2.07 | 38.37 | 0.29 |
| 2000/01 | 33.22 | 21.25 | 54.47 | 13.98 | 0.71 | 39.45 | 0.33 |
| Average | 19.65 | 20.54 | 40.19 | 7.07 | 0.85 | 31.77 | 0.50 |
| Median | 20.65 | 22.69 | 44.78 | 7.05 | 0.76 | 37.18 | 0.48 |

** Wasim modelled data*

**Table E. 5. Water balance components for Tenandra irrigation scheme (GL).**

| | Water Inputs | | | Water Outputs | |
|---|---|---|---|---|---|
| Year | Diversions | Rainfall | Total Input Water | Farm Deliveries | Unaccounted for Water |
| 1995/96 | 12.00 | 0.50 | 12.50 | 9.84 | 2.66 |
| 1996/97 | 24.00 | 0.45 | 24.45 | 20.40 | 4.05 |
| 1997/98 | 31.00 | 0.30 | 31.30 | 26.35 | 4.95 |
| 1998/99 | 21.11 | 0.41 | 21.51 | 17.73 | 3.78 |
| 1999/00 | 28.94 | 0.49 | 29.43 | 24.02 | 5.41 |
| 2000/01 | 40.63 | 0.44 | 41.08 | 33.73 | 7.35 |
| Average | 26.28 | 0.43 | 26.71 | 22.01 | 4.70 |
| Median | 26.47 | 0.45 | 26.94 | 22.21 | 4.50 |

**Table E. 6. Water balance components for irrigated cotton crop farms within Tenandra irrigation scheme (GL).**

| | Water Inputs | | | Water Outputs | | | |
|---|---|---|---|---|---|---|---|
| Year | Rainfall | Irrigation Water | Total Input Water | Surface Runoff | Deep Drainage | Crop Water Use | Soil Moisture Change |
| 1995/96 | 13.93 | 18.22 | 32.15 | 5.84 | 0.31 | 24.46 | 1.53 |
| 1996/97 | 42.77 | 37.93 | 80.70 | 15.40 | 2.05 | 67.08 | -3.83 |
| 1997/98 | 31.92 | 66.93 | 98.85 | 9.47 | 1.30 | 86.47 | 1.61 |
| 1998/99 | 56.48 | 63.95 | 120.43 | 19.08 | 1.96 | 93.01 | 6.38 |
| 1999/00 | 58.32 | 58.00 | 116.32 | 18.48 | 4.98 | 92.17 | 0.69 |
| 2000/01 | 79.82 | 51.05 | 130.87 | 33.60 | 1.70 | 94.78 | 0.79 |
| Average | 47.21 | 49.35 | 96.55 | 16.98 | 2.05 | 76.33 | 1.19 |
| Median | 49.63 | 54.52 | 107.59 | 16.94 | 1.83 | 89.32 | 1.16 |

** Wasim modelled data*

**Table E. 7. Water balance components for Buddah Lake irrigation scheme (GL).**

| | Water Inputs | | | Water Outputs | |
|---|---|---|---|---|---|
| Year | Diversions | Rainfall | Total Input Water | Farm Deliveries | Unaccounted for Water |
| 1995/96 | 11.41 | 0.19 | 11.60 | 10.61 | 0.99 |
| 1996/97 | 19.98 | 0.17 | 20.16 | 19.10 | 1.05 |
| 1997/98 | 27.46 | 0.12 | 27.57 | 26.36 | 1.22 |
| 1998/99 | 20.73 | 0.16 | 20.89 | 20.01 | 0.88 |
| 1999/00 | 24.61 | 0.19 | 24.79 | 23.87 | 0.93 |
| 2000/01 | 28.22 | 0.17 | 28.39 | 27.09 | 1.30 |
| Average | 22.07 | 0.17 | 22.23 | 21.17 | 1.06 |
| Median | 22.67 | 0.17 | 22.84 | 21.94 | 1.02 |

**Table E. 8. Water balance components for irrigated cotton crop farms within Buddah Lake irrigation scheme (GL)**

| | Water Inputs | | | Water Outputs | | | |
|---|---|---|---|---|---|---|---|
| Year | Rainfall | Irrigation Water | Total Input Water | Surface Runoff | Deep Drainage | Crop Water Use | Soil Moisture Change |
| 1995/96 | 5.97 | 7.81 | 13.77 | 2.50 | 0.13 | 10.48 | 0.65 |
| 1996/97 | 18.33 | 16.25 | 34.59 | 6.60 | 0.88 | 28.75 | -1.64 |
| 1997/98 | 13.68 | 28.68 | 42.36 | 4.06 | 0.56 | 37.05 | 0.69 |
| 1998/99 | 24.20 | 27.41 | 51.61 | 8.18 | 0.84 | 39.86 | 2.73 |
| 1999/00 | 24.99 | 24.86 | 49.85 | 7.92 | 2.13 | 39.50 | 0.29 |
| 2000/01 | 34.21 | 21.88 | 56.08 | 14.40 | 0.73 | 40.62 | 0.34 |
| Average | 20.23 | 21.15 | 41.38 | 7.28 | 0.88 | 32.71 | 0.51 |
| Median | 21.27 | 23.37 | 46.11 | 7.26 | 0.79 | 38.28 | 0.50 |

** Wasim modelled data*

**Table E. 9. Water balance components for Greenhide irrigation scheme (GL).**

| | Water Inputs | | | Water Outputs | |
|---|---|---|---|---|---|
| Year | Diversions | Rainfall | Total Input Water | Farm Deliveries | Unaccounted for Water |
| 1995/96 | 3.00 | 0.10 | 3.10 | 3.00 | 0.10 |
| 1996/97 | 4.28 | 0.09 | 4.37 | 4.28 | 0.09 |
| 1997/98 | 5.39 | 0.06 | 5.45 | 5.39 | 0.06 |
| 1998/99 | 4.39 | 0.08 | 4.47 | 4.39 | 0.08 |
| 1999/00 | 4.96 | 0.10 | 5.06 | 4.96 | 0.10 |
| 2000/01 | 5.50 | 0.09 | 5.59 | 5.50 | 0.09 |
| Average | 4.59 | 0.09 | 4.67 | 4.59 | 0.09 |
| Median | 4.68 | 0.09 | 4.76 | 4.68 | 0.09 |

**Table E. 10. Water balance components for irrigated cotton crop farms within Greenhide irrigation scheme (GL).**

| | Water Inputs | | | Water Outputs | | | |
|---|---|---|---|---|---|---|---|
| Year | Rainfall | Irrigation Water | Total Input Water | Surface Runoff | Deep Drainage | Crop Water Use | Soil Moisture Change |
| 1995/96 | 0.83 | 1.09 | 1.93 | 0.35 | 0.02 | 1.47 | 0.09 |
| 1996/97 | 2.56 | 2.27 | 4.84 | 0.92 | 0.12 | 4.02 | -0.23 |
| 1997/98 | 1.92 | 4.02 | 5.93 | 0.57 | 0.08 | 5.19 | 0.10 |
| 1998/99 | 3.38 | 3.83 | 7.22 | 1.14 | 0.12 | 5.57 | 0.38 |
| 1999/00 | 3.50 | 3.48 | 6.98 | 1.11 | 0.30 | 5.53 | 0.04 |
| 2000/01 | 4.79 | 3.06 | 7.85 | 2.01 | 0.10 | 5.68 | 0.05 |
| Average | 2.83 | 2.96 | 5.79 | 1.02 | 0.12 | 4.58 | 0.07 |
| Median | 2.97 | 3.27 | 6.46 | 1.02 | 0.11 | 5.36 | 0.07 |

** Wasim modelled data*

For Narromine irrigation scheme, the median volume of water that was delivered to the farms irrigation scheme over the 6 year period (1995/96 – 2000/01) is 28.12 GL or approximately 80% of the medium volume of scheme total input water (scheme available water). The median volume of unaccounted for water for the scheme is 7.37 GL or approximately 21% of the median volume of total input water.

The median volume of water that is delivered to the farms within Tenandra irrigation scheme is 22.21 GL or approximately 82% of the medium volume of scheme total input water (scheme available water). The median volume of unaccounted for water over the study period (1995/96 – 2000/01) is 4.50 GL or approximately 17% of the medium volume of total input water.

For Buddah Lakes irrigation scheme, the median volume of water that is delivered to the farms is 21.94 GL or approximately 96% of the medium volume of scheme total input water (scheme available water). The median volume of unaccounted for water over the 6 year period (1995/96 – 2000/01) is 1.02 GL or approximately 4% of the medium volume of total input water.

The median volume of water that is delivered to the farms within Greenhide irrigation scheme is 4.68 GL or approximately 98% of the medium volume of scheme total input water (scheme available water). The median volume of unaccounted for water over the 6 year period (1995/96 – 2000/01) is 0.09 GL or approximately 2% of the medium volume of total input water. This volume of unaccounted for water is mainly attributed to evaporation, deep drainage, illegal extraction (if applicable), ground water (if applicable) and measurement error.

The volume of unaccounted for water is mainly attributed to evaporation, deep drainage, illegal extraction (if applicable), ground water (if applicable) and measurement error. The volume of water that evaporates from channels and storage may re-appear as rainwater within the channels and it is a chance event if the rainfall is recovered. It is unknown how much evaporation would re-appear as rainwater within the channel.

It is very difficult to link water lost by evaporation to rainfall that falls within the catchment. Volume of deep drainage from the channels and storage may end up in the shallow groundwater. Measurement errors include mainly the pumping error. Elimination or reduction in pumping error may not save any water but will allow for a better accounting of water use within the Irrigation scheme. Water may also be lost as result of illegal and ground water extraction (if applicable). There may be potential water savings at the farm scale in the Macquarie valley if deep drainage and evaporation from farm channels and storages are minimised. It is very difficult to estimate these volumes of water given the fact that the work undertaken for this project has not done a more detailed calculation and portioning of the volume of unaccounted for water (i.e. water illegally extracted, evapotranspiration, deep drainage, ground water etc).

### Farm Scale

#### Impact of input water and the quantified water outputs on unaccounted for water

It is of interest to investigate the impact of the volume of input water and the sum of outputs on the volume of unaccounted for water when a multiple scale approach is used. Accordingly, the master Bayesian network (BN) shown in Figure E. 1 was expanded and utilised to identify the impact of water inputs (i.e. catchment and scheme water inputs) and water outputs (i.e. diversions, deliveries and end of system flows) on the volume of unaccounted for water. The links between the spatial scales were identified and the BN set to the states representing the actual (current) situations based on the water balances. The BN was compiled after incorporating files that contained water balance data shown in the tables above. Figure E. 2 shows the BN that has been compiled after incorporating files that contained water balance data for period of 6 years (1995 to 2000) for irrigated cotton when water is diverted form the Macquarie river to Narromine irrigation scheme. It should be noted however, that a factor of 100 has been used to convert all water balance values for catchment scales. For example, 3 – 6 GL means 300 – 600 Gigalitres at the catchment scale.

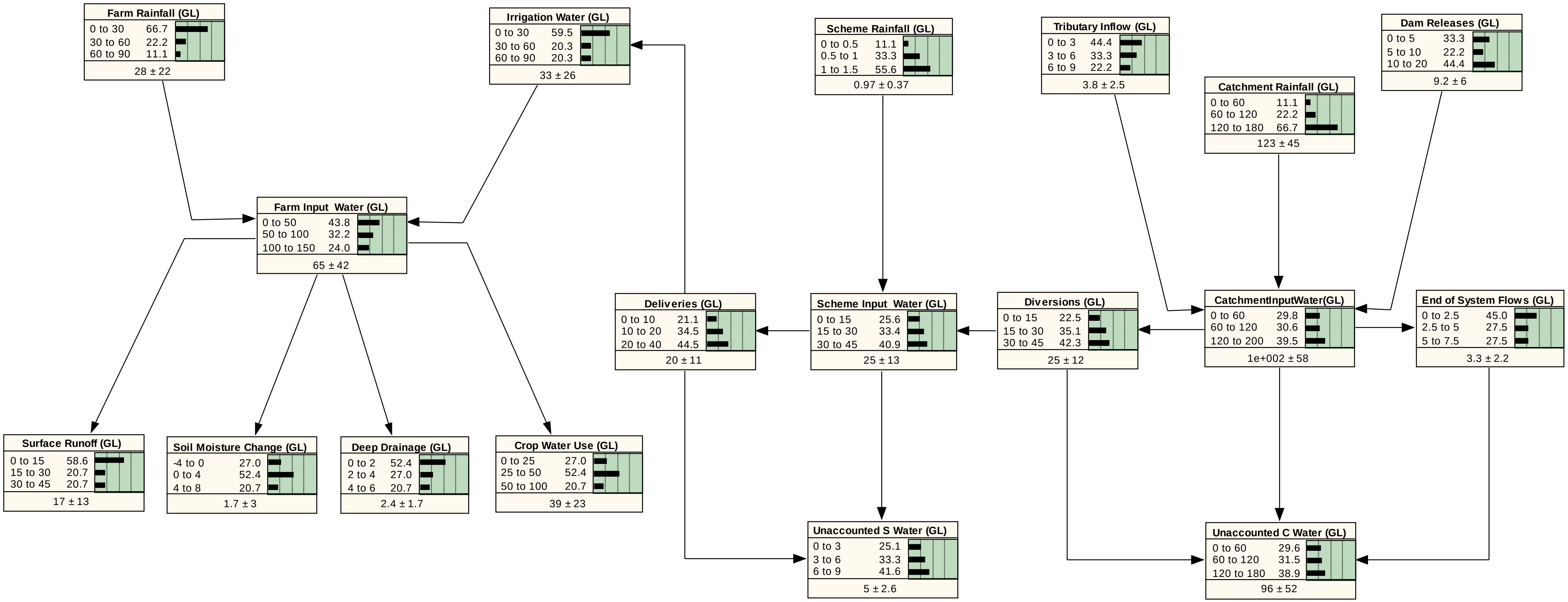


**Figure E. 2 Macquarie valley Bayesian network showing whole of system water balance probability distribution**

It can be seen from this figure that for Narromine irrigation scheme, there is a 25.1% chance that unaccounted for water for scheme scale (SUW) will be between 0 – 3 GL, a 33.3% chance that SUW will be between 3 – 6 GL and a 41.6% chance that SUW will be between 6 – 10 GL. For catchment scale, the results show that there is a 29.6% chance that catchment unaccounted for water (CUW) will be between 0 – 60 GL, a 31.5% chance that CUW will be between 60 – 120 GL and a 38.9% chance that CUW will be between 120 – 180 GL.

Similarly, for Tenandra irrigation scheme, it was found that there is a 29.2% chance that unaccounted for water for scheme scale (SUW) will be between 0 – 3 GL, a 40.8% chance that SUW will be between 3 – 6 GL and a 30% chance that SUW will be between 6 – 10 GL. For catchment scale, the results show that there is a 30.3% chance that catchment unaccounted for water (CUW) will be between 0 – 60 GL, a 32.3% chance that CUW will be between 60 – 120 GL and a 37.4% chance that CUW will be between 120 – 180 GL.

Observed conditional probability results for Buddah Lakes irrigation scheme indicated that there is a 49% chance that unaccounted for water for scheme scale (SUW) will be between 0 – 3 GL, a 25.5% chance that SUW will be between 3 – 6 GL and a 25.5% chance that SUW will be between 6 – 10 GL. For catchment scale, the results show that there is a 29.6% chance that catchment unaccounted for water (CUW) will be between 0 – 60 GL, a 31.5% chance that CUW will be between 60 – 120 GL and a 38.9% chance that CUW will be between 120 – 180 GL.

When water is diverted form the river system to Greenhide irrigation scheme, there is a 51.4% chance that unaccounted for water for scheme scale (SUW) will be between 0 – 3 GL, a 24.3% chance that SUW will be between 3 – 6 GL and a 24.3% chance that SUW will be between 6 – 10 GL. For catchment scale, the results show that there is a 29% chance that catchment unaccounted for water (CUW) will be between 0 – 60 GL, a 30.9% chance that CUW will be between 60 – 120 GL and a 40.1% chance that CUW will be between 120 – 180 GL.

It can be seen from these analyses that the conditional probabilities for the unaccounted for water at scheme and catchment scale have some variations between them but broadly agree with each other. The greatest variation in the chance that high volume of water will be lost and/or obtained at scheme scale occurred under Narromine irrigation scheme with the highest chance of 41.6% that unaccounted for water will be between 6 – 10 GL. Since the volume of unaccounted for water is mainly attributed to deep drainage and evaporation, then this can probably be explained by the fact that Narromine irrigation scheme is a relatively large scheme with a total length of approximately 350 km of delivery channels and a total area of 120, 000 ha (Elliot 1995). These would be expected to have some effect on the volume of unaccounted for water that will be lost. Even a slight change in the delivery channels can affect the rate of evaporation and deep drainage considerably. Mitchell (2002) stated that the deep drainage from the channels may flow to an alluvial aquifer located 50m-110m deep (Keshwan and O'Shaughnessy 1999). There are links between the Macquarie River and an alluvial aquifer that underlies the Macquarie Valley (Keshwan and O'Shaughnessy 1999) but the volume of water that flows into that aquifer has not been quantified for this study. Water from this aquifer is pumped by irrigators in the Narromine irrigation system. Research conducted on the area show that the groundwater behaviour of the alluvial aquifer does not show a clear recharge component coincident with rainfall (Keshwan and O'Shaughnessy 1999). There does not appear to be a strong link between the shallow watertable and the alluvial aquifer.

Deep drainage is a real loss from the scheme scale. Deep drainage from the channels may have contributed to the development of a shallow watertable in the Narromine irrigation scheme. Currently the shallow watertable is between 10-30 m deep (Narromine Irrigation Board of Management 2001). Water may be recaptured from this shallow aquifer provided the water in the shallow aquifers is not too saline. This suggests that there may be water savings by the elimination of deep drainage from the Narromine irrigation scheme. For catchment scale, the greatest deviation occurred when water is diverted to Greenhide irrigation scheme with the chance of 40.1% that high volume of water between 120 – 180 GL will be lost. Greenhide irrigation scheme is a relatively small scheme with only 30 km of delivery channels (Hope 2003).

The overall BN results seem to suggest that in general the total volume of water inputs (available water) for both scheme and catchment scales may have minimal impact on the volume of unaccounted for water. This suggests that an intervention aimed at reducing the available water (scheme and catchment input water) is probably not the best way of achieving a reduction in water lost at these scales. Since the volume of unaccounted for water is attributed to deep drainage, evaporation and measurement error, a better potential management strategy might look at alternative ways of promoting conservation options such as evaporation prevention using molecular blankets and lining the irrigation channels and ditches. This also highlights the fact that Narromine irrigation scheme has over the last decade invested heavily in deep drainage reduction work (Narromine Irrigation Board Management 2001).

## Farm Scale Level

### Water Use Efficiency

Figure E. 3 shows the farm scale Bayesian network that was developed based on the water balance and two key management interventions on the farm total water use efficiency. Farm total water use efficiency WUE was calculated as the measure of water used by the crop per available volume of water (rainfall + irrigation) during the year. Modelled water balance data for irrigated cotton crop were fed in BN and set to the states representing the actual situations in the Macquarie valley. The two interventions (soil type and irrigation scheduling) were introduced in the BN because they have an important influence over the choice of irrigation managements.

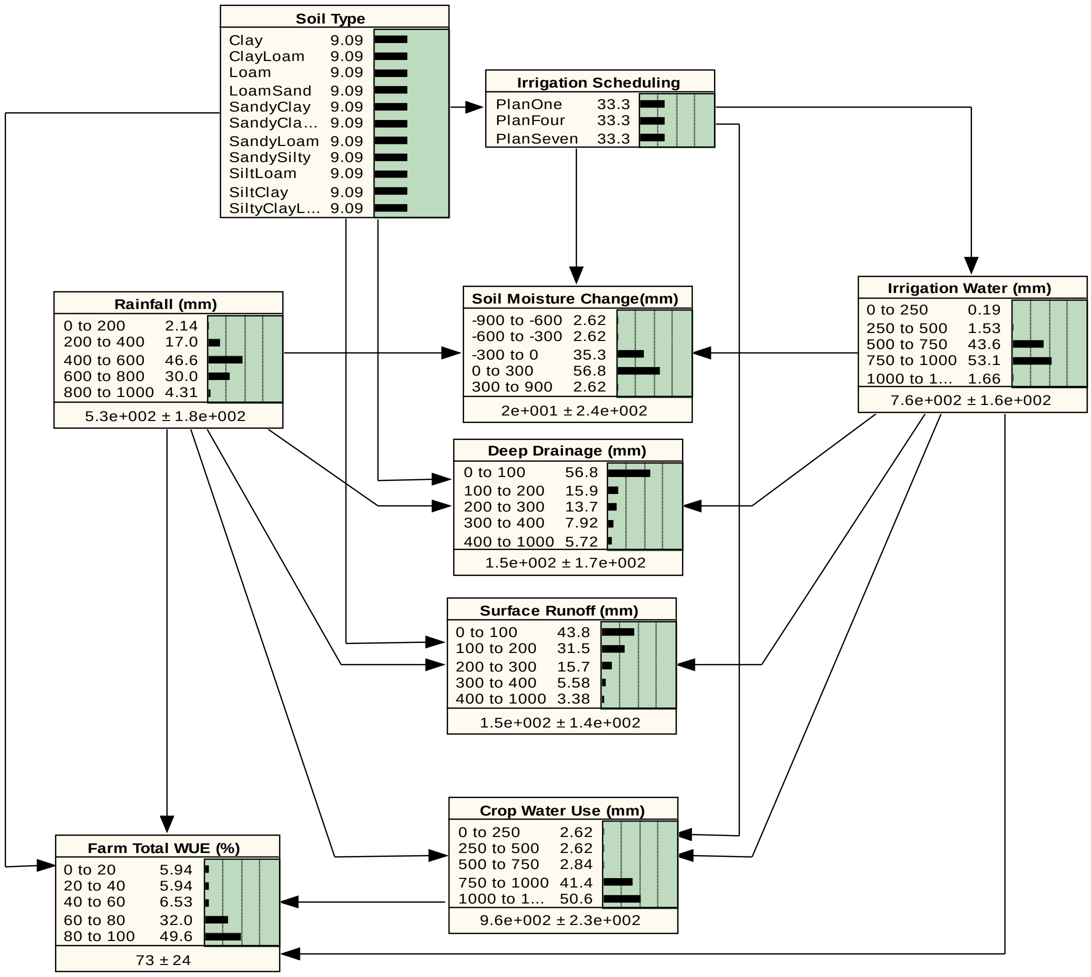


**Figure E. 3. Farm scale Bayesian network diagram for assessment of farm total water use efficiency**

It can be seen from Figure E. 3 that when no intervention is implemented, there is a 49.6% chance that farm total WUE will be between 80% – 100%, a 32% that farm total WUE will be between 60% – 80%, a 6.53% that farm total WUE will be between 40% – 60% and a 5.94% that farm total WUE will be between 0 – 40%. The BN results show that there are relatively small chances of less that 50% for high efficiencies (80% – 100%) indicating that some improvement (management intervention) is needed to lift the efficiencies.

Accordingly, the two interventions (soil type and irrigation scheduling) were implemented to identify their impact on the conditional probabilities of farm total WUE when is in the state 80% – 100% (high efficiency) as shown in Table E. 11. It should be noted that the results in the tables should be read one row at a time. For example, the first row (bold) in table 5.10 should read that "If the soil type is clay, irrigation schedule is plan one, then there is 52.3% chance that farm total water use efficiency (FTWUE) will be between 80% – 100%.

**Table E. 11 Conditional probabilities for the state 80% – 100% (High Efficiency) of the farm total WUE node in Figure E. 3.**

| Soil Type | Irrigation Scheduling | Farm Total Water Use Efficiency |
|---|---|---|
| | | "80 – 100%" (High Efficiency) |
| Clay | Plan one | 52.3% |
| | Plan four | 52.3% |
| | Plan seven | 30.5% |
| | | |
| Clay Loam | Plan one | 55.5% |
| | Plan four | 57.0% |
| | Plan seven | 31.0% |
| | | |
| Loam | Plan one | 62.2% |
| | Plan four | 66.0% |
| | Plan seven | 28.2% |
| | | |
| Loamy Sand | Plan one | 61.2% |
| | Plan four | 65.2% |
| | Plan seven | 26.7% |
| | | |
| Sandy Clay | Plan one | 62.0% |
| | Plan four | 64.5% |
| | Plan seven | 33.0% |
| | | |
| Sandy Clay Loam | Plan one | 56.3% |
| | Plan four | 57.8% |
| | Plan seven | 30.8% |
| | | |
| Sandy Loam | Plan one | 60.9% |
| | Plan four | 65.2% |
| | Plan seven | 25.3% |
| | | |
| Sandy Silty | Plan one | 60.4% |
| | Plan four | 64.2% |
| | Plan seven | 27.0% |
| | | |
| Silt Loam | Plan one | 61.0% |

| | | |
|---|---|---|
| | Plan four | 64.9% |
| | Plan seven | 27.9% |
| | | |
| Silty Clay | Plan one | 54.0% |
| | Plan four | 55.0% |
| | Plan seven | 32.5% |
| | | |
| Silty Clay Loam | Plan one | 55.6% |
| | Plan four | 56.9% |
| | Plan seven | 33.0% |

It can be seen from these tables (5.10 – 5.12), that there are relatively higher chances that high efficiencies (80% – 100%) can be achieved in almost all soils if irrigation schedule plan four (irrigating at fixed depletion of 50% total available water, and at fixed amount of 100mm) is implemented as compared to irrigation plan one (irrigating at fixed deficit of 50 mm, and at fixed amount of 100 mm) and plan seven (Irrigating at a fixed interval of 10 days, and at fixed amount of 30mm). This seems to suggest that irrigation plan four is a more accurate scheduling plan than the other two schedule plans.

What can be concluded from above is that the BN results seem to suggest that high water use efficiencies can be achieved on all soils provided suitable irrigation schedules and/or plans are implemented. However, it should be noted that although some soils demonstrated relatively higher farm total water efficiencies, there are other factors that come into play when determining higher water use efficiencies such as soil health, irrigation systems and economic factors that need to be considered.

### Crop Water Use

Figure E. 4 and Figure E. 5 compare two farm scale BN showing the impact of high rainfall and irrigation water events (400mm – 900 mm) on crop water use for different irrigated crops within different irrigation schemes. The BN results in Figure E. 4 show conditional probabilities for irrigated wheat whereas Figure E. 5 show that of irrigated pasture crops grown within Buddah Lakes and Greenhide irrigation scheme. Crop water use is the total amount of water used by the crop on the farm during the year. It includes evaporation from the bare soil and transpiration via the plant.

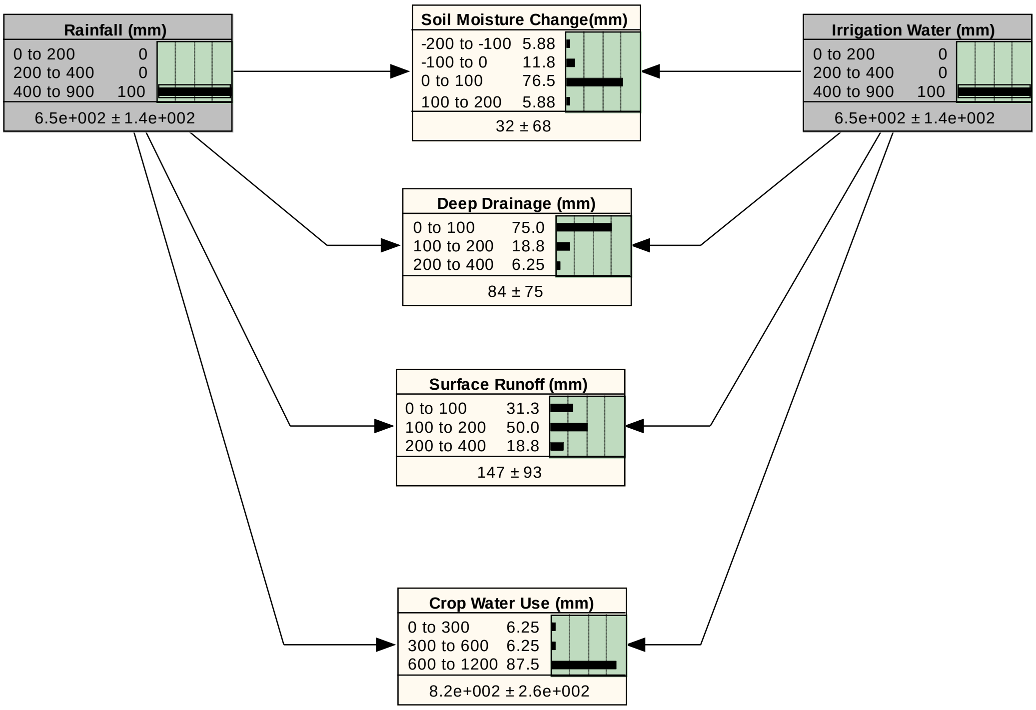


**Figure E. 4. Bayesian network showing the impact of rainfall and irrigation water on crop water use for irrigated wheat.**

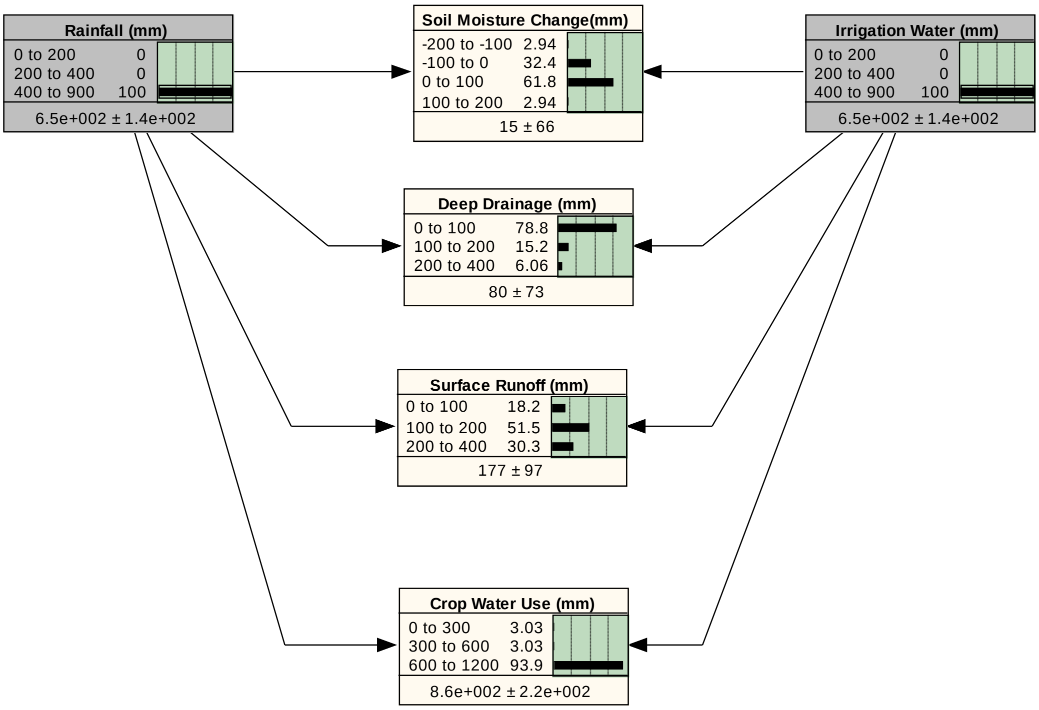


**Figure E. 5. Bayesian network showing the impact of rainfall and irrigation water on crop water use for irrigated pasture.**

It can be seen that for irrigated wheat crop, there is a chance of about 87.5% that water use will be between 600mm – 1200mm, a 6.25% chance that crop water use will be between 0 – 300mm and

300mm – 600mm respectively. For irrigated pasture there is a 93.9% chance that water use will be between 600mm – 1200mm, a 3.03% chance that crop water use will be between 0 – 300mm and 300mm – 600mm respectively. In comparison, the conditional probabilities associated with the node "crop water use" in Figure E. 4 show that high rainfall and irrigation events on wheat crops is likely to have a comparatively lesser impact on water use as compared to the pasture crops.

Tables 5.15 to 5.18 present the conditional probabilities showing the impact of high rainfall and irrigation water on crop water use for different irrigated crops within different respective irrigation schemes for Macquarie valley.

**Table E. 12. Conditional probabilities table for the state "high" of the node "Crop water use" for different irrigated crops within Trangie-Nevertire irrigation scheme.**

| Crop Type | Rainfall | Irrigation Water | Crop Water Use | | |
|---|---|---|---|---|---|
| | | | 0-300mm | 300mm-600mm | 600mm-1200mm |
| **Canola** | **High** | **High** | **1.43%** | **71.4%** | **14.3%** |
| Soybean | High | High | 2.22% | 13.2% | 84.4% |
| Sunflower | High | High | 3.13% | 3.13% | 93.8% |

**Table E. 13. Conditional probabilities table for the state "high" of the node "Crop water use" for different irrigated crops within Narromine irrigation scheme**

| Crop Type | Rainfall | Irrigation Water | Crop Water Use | | |
|---|---|---|---|---|---|
| | | | 0-300mm | 300mm-600mm | 600mm-1200mm |
| Cotton | High | High | 1.33% | 1.33% | 97.3% |
| Lucerne | High | High | 33.3% | 33.3% | 33.3% |

**Table E. 14. Conditional probabilities table for the state "high" of the node "Crop water use" for different irrigated crops within Nevertire irrigation scheme.**

| Crop Type | Rainfall | Irrigation Water | Crop Water Use | | |
|---|---|---|---|---|---|
| | | | 0-300mm | 300mm-600mm | 600mm-1200mm |
| Potatoes | High | High | 33.3% | 33.3% | 33.3% |
| Tomatoes | High | High | 2.38% | 2.38% | 95.2% |
| Grapes | High | High | 2.33% | 2.33% | 95.3% |

**Table E. 15. Conditional probabilities table for the state "high" of the node "Crop water use" for different irrigated crops within Tenandra and/or Marthaguy irrigation scheme.**

| Crop Type | Rainfall | Irrigation Water | Crop Water Use | | |
|---|---|---|---|---|---|
| | | | 0-300mm | 300mm-600mm | 600mm-1200mm |
| Barley | High | High | 3.85% | 3.85% | 92.3% |
| Perennial Pasture(RD) | High | High | 2.17% | 2.17% | 95.7% |
| Citrus | High | High | 2.17% | 2.17% | 95.7% |

*RD = Rotational dairy*

Table E. 12 compares the conditional probabilities showing the impact of high rainfall and irrigation water on crop water use for irrigated canola, soybean and sunflower crops grown within Trangie-Nevertire irrigation scheme. The results reflects the fact that canola crops are likely to have a comparatively much lower water use as compared to the sunflower and soybean crops. There is a relatively much lower chance of 14.3% that high crop water (600mm – 1200mm) will be used for canola crops whereas there are 84.4% and 93.8% chances that high crop water will be used for soybean and sunflower crops respectively.

The conditional probabilities in Table E. 13 show the impact of high rainfall and irrigation water events on crop water use for irrigated cotton and lucerne crops grown within Narromine irrigation scheme whereas those in Table E. 14 show the impact of high rainfall and irrigation water on crop water use for irrigated potatoes, tomatoes and grapes grown within Nevertire irrigation scheme. Similar trends of results were obtained indicating that there is relatively higher chance of 97.3% that high crop water (600mm – 1200mm) will be used for irrigated cotton crops as compared to a 33.3% chance that high crop water (600mm – 1200mm) will be used for lucerne crops. There is a 95.3% chance that high crop water (600mm – 1200mm) will be used for irrigated grapes and a 95.2% chance that high crop water (600mm – 1200mm) will be used for irrigated tomatoes as compared to a 33.3% chance that high crop water (600mm – 1200mm) will be used for potato crops.

The impact of high rainfall and irrigation water events on crop water use for irrigated barley, perennial pasture (rotational diary) and citrus crops within Tenandra an/or Marthaguy irrigation scheme are shown in Table E. 15. It can be seen that for these crops, there is a 95.7% chance that high crop water (600mm – 1200mm) will be used for both perennial pasture (rotational diary) and citrus crops and a 92.3% chance that high crop water will be used for barley crops. The BN results seem to suggest that although when irrigating both perennial pasture (rotational diary) and citrus crops there are relatively higher chances of using more water, barley crops are not too far behind. In other words, in the case of high rainfall and irrigation water events, perennial pasture (rotational diary) and citrus crops use not much more water as compared to barley crops.

The BN results are in line with other available literatures which show that different crops require different amount of water needed to meet the water loss through evapotranspiration (ET). For example, a crop such as cotton, which completely covers the ground at maturity and has many leaves to transpire from, will use more water (high ET values) than say grapes which are trained along tensioned wires and do not present such an area for transpiration. The latter will become subject to moisture stress at a much sooner stage as the soil moisture is depleted. The irrigator will endeavour to avoid plant water stress and information on ET values will help to determine water requirements and/or irrigation scheduling of different crops.

## SCHEME SCALE LEVEL

### Water Use Efficiency

Figure E. 6 shows the scheme scale BN representing the impact of the volume of water inputs and volume of water delivered to the farms on water conveyance efficiency (scheme WUE). Water conveyance efficiency is the efficiency of the scheme system to deliver water to the farm. i.e., the ratio between the water delivered to the farm gate against the amount of water diverted from the Macquarie river. The conditional probabilities shown in figures 5.6 were obtained when the BN was compiled with no intervention implemented after incorporating files that contained data on water balance variables for Narromine irrigation scheme. Table E. 16 presents that for Tenandra, Buddah Lakes and Greenhide irrigation schemes.

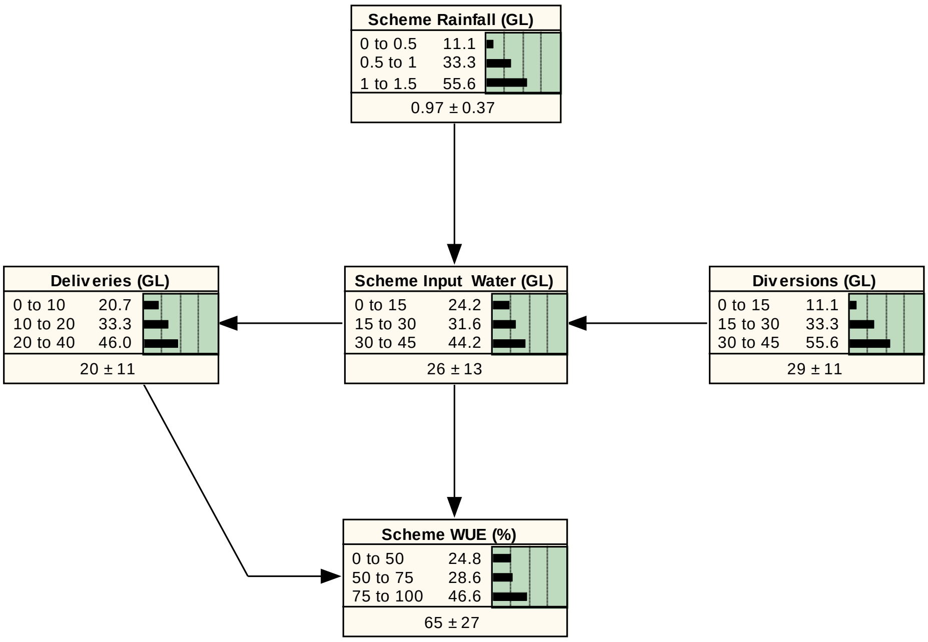


**Figure E. 6. Scheme scale Bayesian network diagram for assessment of scheme water use efficiency**

**Table E. 16 Conditional probabilities for the scheme water use efficiency**

| Scheme WUE | 0 – 50% | 50% – 75% | 75% – 100% |
|---|---|---|---|
| Buddah Lakes | 24.8% | 24.8% | 50.4% |
| Tenandra | 25.8% | 25.8% | 48.5% |
| Greenhide | 22.9% | 22.9% | 54.1% |

*Scheme WUE: scheme water conveyance efficiency*

It can be seen that the best result is produced when water is delivered to the farms via Greenhide irrigation scheme where there is a 22.9% chance that scheme water conveyance efficiency (Scheme WUE) will be between 0 – 50%, a 22.9% chance that scheme WUE will be between 50% – 75 % and a 54.1% chance that scheme WUE will be between 75% – 100%.

The BN result seems to suggest that the efficiency levels that are experienced in the Greenhide irrigation scheme are bit higher than those of the other irrigation schemes. This result reinforces the fact that Greenhide irrigation scheme is a relatively small scheme with only 30 km of delivery channels (Hope 2003) and covers a much smaller area compared to other schemes. It is important to consider the fact that a large percentage (not yet quantified) of the water lost in the delivery of water within these irrigation schemes will be attributed to evaporation and deep drainage.

### CATCHEMENT SCALE LEVEL

### Catchment Input Water

The developed catchment scale BN was used in a "diagnostic mode" whereby the management objectives are changed and the impacts on the interventions examined. Figure E. 7 shows the results obtained when the BN is used this way to examine the impacts of unaccounted for water on the input water for this scale. In other words, the states of catchment unaccounted for water (variable at the head of arrows) were changed to examine the impacts on the volume of catchment input water (variable at the base of arrows). Catchment input water is the total amount of water inputs and/or inflows (dam releases, rainfall and tributary inflows) that entered the catchment system during the year. The water balance data collected for catchment scale were utilised in the BN after a factor of 100 was used to convert all water balance values at this scale.

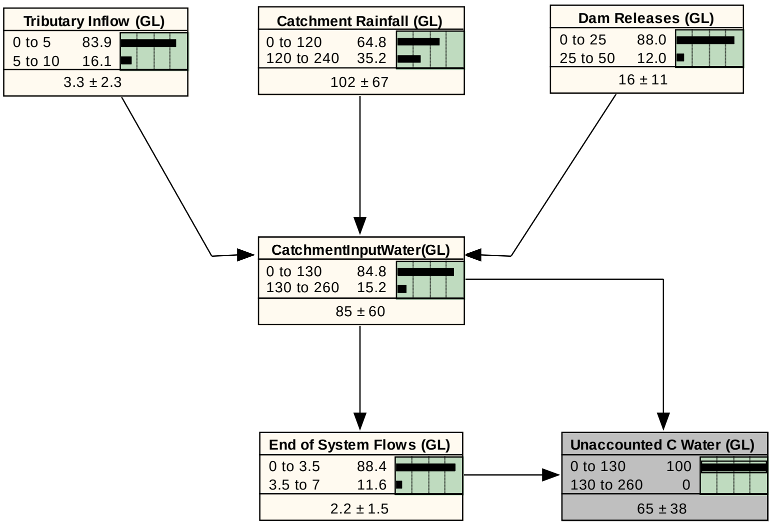


**Figure E. 7. Bayesian network representing water balance variable for Macquarie catchment.**

Unlike in the previous work where the BN's were used in a predictive mode, when used in a "diagnostic mode", it is very hard to interpret the results. The correct interpretation of the BN result in Figure E. 7 is that given the different yearly water inputs (incoming water flux situations) and end of system outflows in the Macquarie catchment, then out of those situations which had low volume of catchment unaccounted for water (CUW) between 0 – 130 GL, 84.8% of the water inputs would be between 0 – 130 GL and 15.2% of them would be between 130 – 260 GL. Similarly, 88.4% of the end of system flows would be between 0 – 3.5 GL and 11.6% of them would be between 3.5 – 7 GL.

It would be wrong to interpret the results as in the previous examples that uses the BN in a predictive mode with the conclusion that low volume of catchment unaccounted for water between 0 – 130 GL (100%) will be obtained when 84.8% of the catchment input water is between 0 – 130 GL and 15.2% of the catchment input water is between 130 – 260 GL; and/or when 88.4% of the end of system flows is between 0 – 3.5 GL and 11.6% of the end of system flows is between 3.5 – 7 GL. This is incorrect as shown in Figure E. 8 where the conditional probabilities of "catchment input water and end of system flows" have been fixed to these values. It can be seen that when the catchment input water and the end of system flows are in this states, then there is only a chance of 74.7% (not 100%) that CUW will be between 0 – 130 GL and a 25.3% chance that CUW will be between 130 – 260 GL

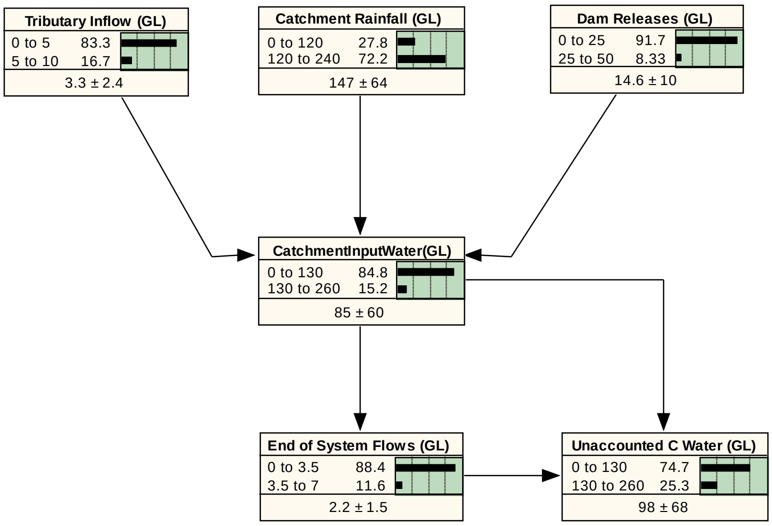


**Figure E. 8. Bayesian network representing water balance variable for Macquarie catchment.**

Figure 5.7 (a) and (b) show that the catchment scale BN representing the impact of catchment input water and end of system flows on the catchment unaccounted for water. The results of only three nodes are shown (other nodes have been divorced).

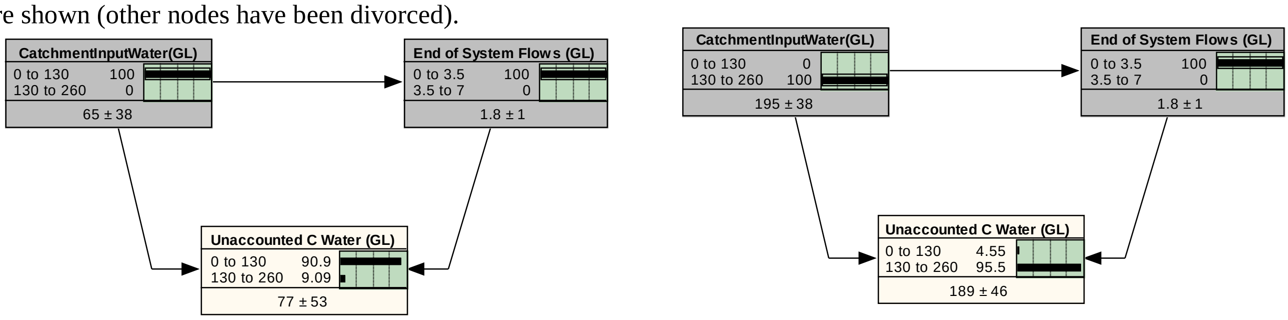


**Figure E. 9. Effect of catchment input water on unaccounted for catchment water when end of system flows are low between 0 – 3.5 GL.**

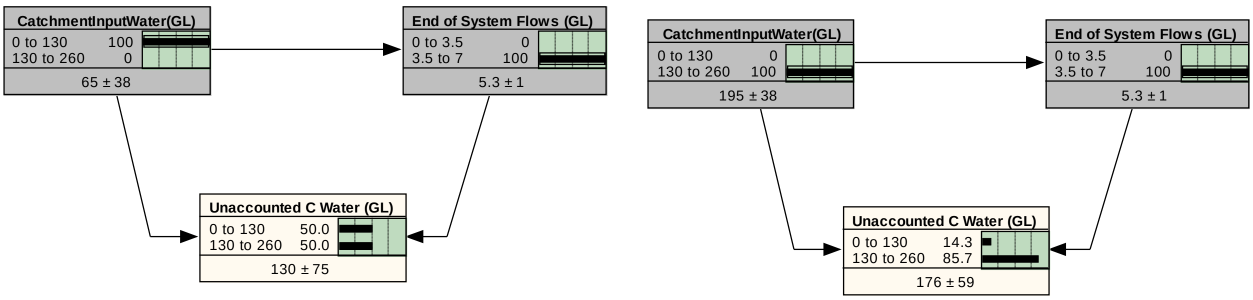


**Figure E. 10. Effect of catchment input water on unaccounted for catchment water when end of system flows are high between 3.5 – 7 GL.**

Figure E. 9 shows the same BN with node “catchment input water” changed from low “0 – 130 GL” to high “130 GL – 260 GL”. It can be seen from this figure that when end of system flows are low “0 – 35 ML”, the increase in catchment input water leads to relatively big increase in the chance (86.41%) that higher catchment unaccounted for water will be obtained. However, Figure E. 10 shows that when end of system flows are high “3.5ML – 7ML”, the impact of increasing water catchment input water is much smaller (35.7%). This BN results seem to suggest that an intervention aimed at increasing the end of system flows will boost the benefits gained from the continuously increasing water catchment input water demands for irrigation purposes. We can conclude that the catchment BN is also useful when an integrated approach to water demands is required as a strategy to meet multiple objectives through a variety of means.

# APPENDIX F: THE FACTORS INFLUENCING CROP PLANTING AND WATERING BEHAVIOUR

Crop planting and watering behaviours are essential processes that involve many crop growth functions (i.e. sowing seeds or setting of crops in the ground, supplying water for crop growth etc) in the production of food and fibre. During these processes, growers are called upon to make management decisions that include but not limited to the type of crop to plant, area of crop to plant, timing of planting, area to irrigate, pre-planting irrigation, irrigation type and irrigation scheduling. These management decisions made by the growers regarding crop planting and watering behaviours can be influenced by socio-economic, climatic and cultural factors. Of particular significance are the socio-economic and climatic factors and these are the two focus areas in this section. The socio-economic and climatic factors influencing crop planting and watering behaviours can be categorised as:

(1) Water availability
(2) Soil type
(3) Finances
(4) Technologies
(5) Salinity
(6) Weeds and pests
(7) Labour requirements
(8) Saving time
(9) Crop rotation pattern
(10) Rainfall
(11) Temperature
(12) Crop evapotranspiration
(13) Extreme events

The influences of these factors, unless managed well, can devastate crop planting and watering practices, economies and communities and can retard long-term economic development. It is therefore crucial during such times to make the best possible decisions such as emphasizing improved crop planting practices and positive irrigation behaviour. The following is a discussion covering these areas, and highlighting their relevance to the present project "Determining whole of system water use efficiency for Macquarie and Murrumbidgee river valleys.

It is however, acknowledged that irrigated agriculture in Australia is nested in a cultural context as well as a socio-economic one. The cultural "influences" can be very local and can help determine what is regarded as good farming practices in the area. No research work on the cultural influences and/or factors was undertaken. These were considered to be beyond the scope of the work undertaken for this project.

### Available Water

Available water is the potential water from any source (i.e. regulated and unregulated rivers, groundwater, farm dams and/or storages, town water supplies, allocations, water traded and soil moisture storages) that is available to the crop at some stage during the growth cycle. The readily available water (RAW) is the difference between field capacity and refill point (usually determined as half way between field capacity and wilting point) and is a measure of water available to crop roots. The actual rooting depth of the crop will determine the readily available water. For example, if the rooting depth is 1.5 m and the available water is 50mm/m then the readily available water to the crop is 75mm. The available water influences several crop planting and watering behaviours and decisions relating to what area of crop to plant, type of crop to plant, timing of crop planting, area to irrigate, pre-planting irrigation, irrigation scheduling and irrigation type.

Generally, if available water is not limited, the area of crop planted will be at maximum capacity for a farm. If available water is limited (i.e. available water is less than that required to grow maximum area) then a reduced area will be planted. In Australia, it is a common practice to use some form of crop rotation where two or more crops are grown on the same piece of land in a planned sequence over several seasons. Within each crop rotation pattern there is a "dominant" and "subsidiary" crop around which the decision of what area of crop to plant revolves. Unless there is limited water availability, the dominant crop will be planted to the limit of the area available in the rotation plan (Lyall and Macoun 1994). Water that remains after meeting the requirements of the dominant crops will be used on subsidiary crops often on an opportunistic basis, but this will not cause an increase in area of the dominant crop planted by jumping another rotation pattern.

The type of crop to plant on the farm can be determined by the amount of available water. Some crops are more suited to areas or fields where there are plenty of water available or ponded conditions while others prefer dry condition where there is not much water. For example, rice is grown under ponded conditions until shortly before harvest as rice prefers conditions where there is plenty of water available to achieve maximum production (CSIRO 2000). Yet cotton crops that originated in hot and dry regions (areas with a long hot season) do best in the conditions with limited water availability (Constable 1988). The longer and hotter the season, the higher the potential that high yields of cotton will be obtained.

Even though for all crops, there is a fairly narrow window of the time when they are planted, water availability can influence the timing of crop planting. Lyall and Macoun (1994) stated that if there is water supply shortages or no water available at the planned time of planting, crop planting would be deferred and the ground left in fallow especially for crops such as lucerne and perennial pastures, which are semi-permanent crops typically grown for periods of 2 to 10 years after establishment. However, in some cases a grower may probably go ahead with planting in the expectation of relying on rainfall until irrigation supplies returned to normal. According to CSIRO (2000) water available or water "left over" after the rice harvest determines the timing of planting for other (winter) crops. The timing of winter crops planting is immediately after a rice harvest with the intention of capturing and using the available soil water that remains after the rice harvest that would otherwise have leaked into the water table and/or wasted by draining below the root zone.

The grower's decision of what area to irrigate when there is sufficient availability of water will be to irrigate the full area planted on each occasion. When there is major water shortage, less than the normal area of a crop may be irrigated leaving part of the area in fallow. This practice aims at reducing the area irrigated and applying the normal watering requirement to the reduced area. Lyall and Macoun (1994) stated that with this practice most crops will suffer significant reductions in yield if they are allowed to become stressed and that a 100% crop loss could occur if this is allowed to happen. However, growers aim to ensure a successful crop on at least part of the area they have irrigated, and to take a chance that the remaining area will be rain-fed to give them some return. Another possible strategy may involve sacrificing the subsidiary crops and concentrating on irrigating the dominant crop so that any reduction in its area is minimised.

Pre-planting irrigation is commonly practised in Australia where the soil profile is filled with water to a certain depth shortly before planting. Water availability in the soil prior to planting can affect pre-planting irrigation decisions in that it can significantly reduce or even eliminate this process. If the soil water moisture deficit is fairly small, pre-planting irrigation would not occur. The process is commonly used on crops such as cotton, soybean, maize, sorghum, summer vegetables, wheat and other cereals and not used for establishment of Lucerne or pasture. Wheat and other cereals are frequently grown opportunistically under irrigation, so that if there are limited water supplies, there would be no pre-planting irrigation and the crops are left to develop under rain-fed conditions. The water that is saved would be reserved for the dominant crop in the rotation scheme (Lyall and Macoun 1994).

Irrigation scheduling decisions are heavily influenced by the availability of water. Conceptually, the available water may be thought of as a reservoir of water available to the crop. As the crop transpires, this reservoir is depleted and must be refilled before it reaches a critical level and therefore a need to irrigate. Therefore, the available water heavily influences irrigation scheduling. The general rule of thumb is to aim and irrigate when the depletion of total available water reaches 50% (Faulkner and Jones 1996).

The decision of what irrigation type a farm will install can be influenced by the availability of water. When available water is limited, the growers need to endeavour to be as efficient as possible and make every drop of irrigation water available contribute towards crop production in order to maximise production from their limited water supplies. In this way, the incentive for growers is to adapt and adopt irrigation types that have the potential to increase the beneficial use of available water, such as drip irrigation systems. Therefore, water availability and the need to save available water influences the irrigation system a farm employs or is contemplating to establish. For example, the stone and pome fruit growers in Tumut and Batlow districts of NSW adapted micro-irrigation systems in order to maximise production from their limited water supplies (Kaine and Bewsell 2001).

### Soil Type

Soil may be defined as a medium for crop growth, which provides a supply of water, oxygen for root respiration, soil temperature, low mechanical resistance to root and shoot growth, essential plant nutrients and less salts and toxic materials in order for crops to grow successfully. However, it should be noted that soil is a complex mass of minerals that can have many different definitions. The soil type that exists on an individual farm is a major factor that affects the productions of reliable yields and the decisions relating to what type of crop to plant, area to irrigate, pre-planting irrigation, irrigation scheduling and irrigation type.

Under normal irrigated agriculture, different soil types will suit different types of crops. Table F. 1 presents different types of soils types that suit different types of crops in within the Macquarie valley.

**Table F. 1. Types of crop mainly grown on different types of soils in the Macquarie valley.**

| Soil type | Type of crops mainly planted |
|---|---|
| Older alluvial soils | Lucerne |
| River flats high leaching fraction soils | Lucerne |
| River flats soils | Sweet corn maize |
| Various soils | Cotton |
| Alluvial soils | Citrus |
| Various | Rotation crops for cotton such as: cereals, sunflower, canola, millet, sorghum |
| Various | Green manure crops as rotation for cotton such as fababeans & cereals |
| Hard setting red soils | Grapes |
| New alluvial river flats | Vegetable seed crops |

*Source: Brill et al (2001)*

An area on the farm that is considered to be good for growing crops will be an area where soils are fertile. If the soil is not fertile, the area will need the addition of water and fertilisers. If the soil type is considered fertile, irrigation may not occur or can be significantly reduced. Hence, soil type on an individual farm can influence the decision of what area to irrigate.

Soil type influences the irrigation scheduling plans on an individual farm, specifically in regard to its texture. The texture of a soil is closely related to its water holding capacity or the reservoir of the moisture available for plant use. The water is absorbed by plant roots and must be periodically replenished by rain or irrigation for successful production of crops. Thus, the soil serves as a reservoir for moisture and knowledge of the soil's moisture holding capacity is a principle factor influencing the frequency and amount of water to be applied. Soils with larger available water capacity require less frequent irrigation, such as soils with high clay contents.

Sandy soils have low suction pressure values and low field capacity, thus water is easily extracted and the available water stored is small requiring frequent irrigation. Also, the majority of growers in Australia decide when to irrigate by checking the appearance and condition of the soil. Growers dig into the soil and judge its conditions from its colour and texture, involving squeezing a ball of soil in the hand. By doing this, they indirectly and subjectively assess the water moisture availability in the soil in relation to the crop wilting point. Since most growers recognise that crop yields will be adversely affected as the soil moisture approaches and falls below wilting point, they aim to irrigate when the soil water moisture falls to a little bit above wilting point (Lyall and Macoun 1994).

The impact of different irrigation systems will depend on the soil type and its structure that exists on an individual farm. Kaine and Bewsell (2001) conducted a study on soil monitoring, irrigation scheduling and vegetable production in South Australia, Central and Northern Victoria and in the Murrumbidgee irrigation area (MIA) and found that:

(1) spray watering or drip irrigation better suit undulating country or highly permeable soils,
(2) in the dairy industry, laser graded flood watering suited the soil types and topography in the northern irrigation region of Victoria,

(3) spray watering was more suitable than flood watering on farms with light sandy soils and undulating topography in Macalister irrigation district in Gippsland, and
(4) in the grape industry in Sunraysia, furrow watering was the original method that was used to irrigate vineyards even though the soils are relatively permeable.

The study concluded that the crucial factors driving the choice of the irrigation systems for vegetable production were soil type and topography and that drip irrigation is too expensive to be economically viable on heavy impermeable clay soils, but is viable on light highly permeable sandy soils. It should be noted however that although the impact of irrigation systems depend on soil types, its texture and variability, there are other factors that come into play such as the management requirements that exist on an individual farm.

### Finances

This is loosely defined as the management of disposable income of the growers and other assets including the current marketplace and forecast prices. Since growers aim at maximising profits the decisions relating to what type of crop to plant, area to irrigate and irrigation type are heavily influenced by the finances (income, expected market and economic conditions).

The decision of what type of crop to plant on an individual farm is heavily influenced by finances. If the market for a crop to plant say wheat looks poor growers may switch to planting another crop with better market price say cotton in place of wheat. Some growers may switch from say a three-year crop rotation to a four-year crop rotation, or some other period, in response to perceived market conditions (Lyall and Macoun 1994). In other words, if the market price for cotton looks good they may plant a third year of cotton and delay the wheat crop by a year. Elliot (1995) stated also that many growers that experienced lower commodity prices and higher production costs in the Macquarie valley have changed towards summer crops especially cotton in their irrigation enterprises as a means of remaining financially viable.

The growers decision when the finances for a particular crop look good is to apply the normal watering requirement to the full area of crop planted on each occasion and with the intention of producing maximum yields. When the finances look poor, less than the normal area of a crop may be irrigated. Therefore, finances are considered to be influential over the decision of what area to irrigate.

Finances are the main barrier to the adaptation and adoption of better irrigation type that promote efficient water use and more sustainable faming practices. For instance, although in today's markets drip irrigation systems are well-trusted with many benefits, one of its draw backs is that drip systems are expensive, certainly more expensive than other conventional methods, thus diminishing their advantages over other methods. Postel (1996) assigns a value of $ 1,000 per acre for row crops like vegetables. The high cost of hundreds of emitters required to deliver water to the crops (usually 20 – 25% of the total costs) becomes a barrier and makes drip irrigation unaffordable especially for small growers who cultivate on a small scale. Therefore, the irrigation type a farm has or will have to install is heavily influenced by the finances in the agriculture sector.

What can be suggested from the above is that since growers aim at maximising returns that depends heavily on their own production, increases in their finances may help improve their overall crop productivity.

### Technologies

Since the technologies on an individual farm are normally dictated by the economics, whereby growers often expect higher financial returns for the adoption of new technologies, then it becomes obvious that the decision of what type and area of crop to plant including the crop yield response is influenced by the available technologies. For example, high value crops (e.g. sorghum, sunflowers) or vegetables (e.g. tomatoes) will be planted in response to advanced (higher) technologies and management skill inputs with the intention to achieve high yield with high economic value per hectare. The point here is that the use of advanced technologies is generally expensive and more difficult to manage successfully and therefore the usage of advanced technologies is best suited for high value crops. Table F. 2 below shows different types of irrigation technologies and management options that are predominantly used for the irrigation of different types of crops in the Macquarie valley.

**Table F. 2. Types of irrigation technology used for different crops and management options in the Macquarie valley.**

| Predominant Irrigation type | Type of crops mainly planted |
|---|---|
| Border and spray | Lucerne |
| Sprinkler | Lucerne |
| Furrow and centre pivot spray | Sweet corn maize |
| Furrow and border centre pivot and subsurface drip | Cotton |
| Overhead sprinkler and micro spray | Citrus |
| Furrow or border, centre pivot | Rotation crops for cotton: winter cereals, safflower, canola, millet, sorghum |
| Furrow or border, centre pivot | Green manure crops as rotation for cotton such as fababeans & cereals |
| Surface and drip | Grapes |
| Sprinkler | Vegetable seed crops |

*Source: Brill et al (2001) * management options especially in regard to salinity problems*

The technologies available on an individual farm influence the irrigation scheduling plans. It is well known that successful irrigation scheduling depends mainly upon understanding and utilizing good technologies and management skills. In other words, the more advanced the irrigation technologies and management skill used the easier and simpler it becomes for growers to apply the right amount of water to their crops at the right place and right time. Kaine and Bewsell (2001) stated that the installation and management of pressurised systems such as mini sprinklers and drip irrigation were the most influential factors relating to irrigation scheduling resulting in irrigating more frequently at lower volumes.

It can be said that the use of appropriate technologies have the potential to bring about increased and predictable crop production, enhanced crop quality while reducing farming risks and giving growers greater returns on their produce, however that the technology and management must be right for the situation if sustainable farming practices are to have a chance of success.

### Salinity

Salinity is the existence of concentrated salts in the soil solution making it difficult for crops to take up both water and nutrients for their growth, resulting in reduced crop production. Salinity is a major problem on irrigated agriculture that is difficult to reverse and its management is complicated and requires a whole-of- system approach. Salinity influences the decisions relating to what type and area of crop to plant, area to irrigate and irrigation type.

The decision of what type of irrigation a farm will have to install is recognised as being influence by the salinity condition. When the water supply is saline, and crops are salt sensitive, then irrigation types such as micro systems which can maintain a higher soil water regime, and therefore, a more dilute salt concentration near the emerging seedling for improved stand establishment will be a better choice to install. Saline water may also limit the use of sprinkler irrigation systems if the saline water that drops on the crop leaves will be harmful.

The type of crops planted on an individual farm will also differ significantly in tolerance to concentration of soluble salts in the root zone. Some crops such as citrus and bean crops are generally more sensitive to salts than others, and therefore such crops may not be planted in areas with severe salinity problems (Brill et al 2001). For annual crops germination is likely to be the biggest salinity issue, these crops are very tolerant when established especially the cotton crop.

Build up of soil salinity from saline irrigation water degrades land resulting in a declining soil health and reduced soil fertility and in severe situations bare compacted soils. These will result in reduced crop growth and less area of crop to be planted and irrigated. In the worst case scenario, salinity can force land on an individual farm to be taken out of production completely. Therefore, area of crop to plant and irrigate are influenced by salinity and are some of the main decisions to be made in order to maximise productivity under saline conditions.


 

The influence of salinity on the type and area of crops to plant, area to irrigate and the irrigation type for irrigated agriculture in the Macquarie valley is shown in Table F. 3. The following expert opinions and suggestions were made in addition to the table: (1) Citrus is generally salt sensitive, (2) Subsurface drains could be used on new developments to assist in the management of irrigation and water table rise, (3) Winter cereals, safflower, canola, millet, sorghum, faba beans are mainly grown on irrigation land as rotation crops for cotton, (4) Build up of soil salinity from using saline irrigation water on high water use crops such as cotton will be the biggest salt issue for these crops, (5) For green manure crops as rotation for cotton such as faba beans and cereals, use of salt tolerant rotation crops and varieties, (6) For grapes, wine quality (sodium and chlorine levels in grapes) is likely to be a problem before production is severely affected, (7) Vegetable seed crops are highly sensitive to salinity and (8) Build up of soil salinity may occur even under drip with incorrect application or without the use of adequate leaching fraction.

**Table F. 3. Vulnerability of irrigated agriculture in the Macquarie valley to salinity.**

*Source: Brill et al (2001)*

| Type of crops mainly planted | Predominant system | Relative area in the valley | Sensitivity of system to salts | Vulnerability | Management Options |
|---|---|---|---|---|---|
| Lucerne | Border and spray | Small | Low | Low | Avoid leaf burn by irrigating at night |
| Lucerne | Sprinkler | Small | Low | Perched saline water table may cause problems | |
| Sweet corn maize | Furrow and centre pivot spray | Small | Low | | |
| Cotton | Furrow and border centre pivot and subsurface drip | Large | High | Low | Use of more efficient irrigation practices to prevent the built up of shallow ground water tables |
| Citrus | Overhead sprinkler and micro spray | Small | Various | High | Subsurface drains could be used on new developments to assist in the management of irrigation and water table rise. |
| Rotation crops for cotton such as cereals, canola, millet, sorghum | Furrow or border, centre pivot | Large | Various | High | Use of salt tolerant rotation crops and varieties |
| Green manure rotation crops for cotton such as fababeans & cereals | Furrow or border, centre pivot | Large | High | High | Use of salt tolerant rotation crops and varieties |
| Grapes | Surface and drip | Very Small | Moderate | High | Use of salt tolerant rootstock, water use efficiency to prevent perched water tables |
| Vegetable seed crops | Sprinkler | Small | High | Leaf type vegetables have a low tolerance to salinity | Micro irrigation systems, especially drip increases leaching, mulching soil surfaces. |

Salinity problems remedial measures may be possible but at considerable costs. However, prevention is better than cure, and thorough planning can avoid the worst impact of salinity.


 

### Weeds and Pests

Weeds and pests are unwanted plants, insects and animals that are destructive to cultivated crops. They can degrade land on the farm, bring about a reduction in crops' available moisture, nutrients, sunlight and growing space and cause damage to germinating seeds. Weeds and pests are recognised as having a severe impact on the decisions relating to what type of crop to plant and what type of irrigation a farm will have to install.

Weeds and pests are considered to have a great influence on the growers' decision of what type and area of crop to plant including the choice of crop rotation. For example, in some cases, crops are grown to control weed and improve the soil type. For example, wheat crops are commonly grown after cotton for purposes of weed control and improvement of soil structure (Lyall and Macoun 1994). In other cases, crops say pastures may be planted in areas with some common type of weeds and pests whereas others crops may not. This is mainly because the diseases caused by these weeds and pests in pasture crops may not have the same significance effect as compared to the other crops. In the Macquarie valley, many growers may not grow crops such as maize adjacent to cotton crops because maize breeds heliothis, mites, and other pest that affect cotton crops (Elliott 1995).

The decision of what type of irrigation a farm has or will have to install can be influenced by the presence of weeds and pests. In areas where there is a great threat from weed and pest diseases, irrigation types such as drip systems which are reported to enhance disease control (because their soil moisture and chemical additive levels can be closely controlled) and easily manage the frequency of timing of chemical applications will be better choices to install. Also, with these irrigation types the spread of any existing disease organism by water movement is much less likely since water runoff is eliminated.

Weeds and pests provide an additional financial burden in both lost production and control measures. These burdens should be kept low and the most important aspect of control is early identification, detection, and immediate control since growers will cease irrigating crops where weeds or pests problems become far too great to handle. Affected crops may be thinned or in heavy infestations, so badly damaged that re-planting is necessary. This in turn results in a reduction in crop yields, quality and biodiversity and contributes to extinctions of native crops and increases the risk of bushfire and pesticide resistance.

### Labour Requirement

Labour is the physical or mental work required during crop planting and watering behaviour and its availability is an important factor that comes into play when considering productivity of cropped land whereby having access to sufficient and/or skilled labour is postulated to enhance production capacity. Labour requirement can influence the decisions of what type of crop to plant, area to irrigate and irrigation type a farm has or will have to establish.

Some crops such as soybeans are a labour intensive crop as compared to say rice and to achieve high yields requires good and well timed application of water, chemicals and fertilisers. If available labour is limited, such crop may not be planted. In this way, the decision of what type of crop to plant and irrigate can be influenced by labour requirement.

Labour requirement is recognised as a key factor when considering an irrigation type to be installed on a farm. It is obvious that if a highly automated type of irrigation is in use on an individual farm, then there is little, if any, labour required for operation. Again, If available labour is limited, these types of irrigation (highly automated) where only a significant amount of labour is required mainly during the initial system installation may be of a better choice. McGuckian (1998) stated that the major benefit of changing irrigation type is to reduce labour (ML/labour) which, when combined with any yield increase, allows business to grow.

Inadequate labour and/or lack of access to skilled labour coupled with a time constraint may have implications for pre- and post- harvest losses which limits expansions in the area planted leading to low crop availability at farm level. Crocker (1993) conducted a survey on the grower's perceptions of their major issues on horticultural farms in the Murrumbidgee irrigation area and found that:

(1) many growers found it difficult to hire trained and/or reliable labour for their farm and couldn't afford the wages
(2) several growers in the area were changing their farm practices due to lack of available labour, for example one grower was changing from grapes to citrus and a few were going to mechanical harvesting and sod culture
(3) a few growers were helped by part-time labour, or one permanent man. Larger farms tended to have about 1 worker per 100 acres
(4) farms hired casual labour for picking and pruning
(5) several growers run their farms on a part- time basis, working off-farm during the week or doing grape harvesting contract work
(6) some growers suggested that farm courses need to be improved, and that a training wage should be available, as some growers could not afford to train someone and give them full wages
(7) large vineyard stated that they were aware of the labour problems faced by small farms.

In Australia, the result of labour deficiency is that many of the farms are run by the husband and wife and their sons (if applicable). This highlights a need for more external labour and training (i.e. off the farm) for young generation of irrigation growers. An increase in labour resources will to lead to an increase in productivity of cropped land.

### 1.1.1 Saving Time

Saving time is recognised as a key influential factor over the decisions of what type a farm will have to install. Kaine and Bewsell (2001) carried out some studies on "managing irrigation for grapevines" and "soil monitoring, irrigation scheduling and vegetable production" and found that:
(1) grape growers living in the Sunraysia, Robinvale, Swan Hill, Riverland and MIA regions installed pressurised irrigation technologies in order to save time irrigating.
(2) the need to save time spent watering was particularly apparent in the dairy industry, many dairy farms originally consisted of numerous narrow, short-watering bays with small outlets. Consequently, growers were spending many hours, often at night, changing watering bays and checking on the watering generally. Laser grading allowed growers to consolidate many small bays into a few large bays thereby dramatically reducing the amount of time that needed to be spent watering
(3) growers in the stone and pome fruit industry have redeveloped their orchards and adopted micro-watering in order to save time irrigating, harvesting and spraying, and to increase their flexibility in the timing of these activities. Redevelopment involves planting trees more densely in longer rows using trellising techniques. This enables harvesting to be mechanised saving time and money. Redevelopment requires the adoption of micro- watering, as closer planting layouts are not suited to furrow irrigation. Since the orchard floor remains dry with micro-watering systems, growers are able to irrigate, harvest and spray concurrently with these systems. Hence, their flexibility in timing these activities is enhanced and
(4) growers around Murray Bridge used timers to automate their pumps and sprinkler systems to reduce the time they spent watering.

They pointed out that while there may be other benefits to pressurised technologies, these were secondary to the time, flexibility and labour saving pressurised technologies offer. It should be noted however that the growers need to save time may encompass not only a need to reduce the amount of time needed to devote to the task of crop planting and watering behaviours but also undertaking other productive and domestic activities.

### 1.1.2 Crop Rotation Pattern

Crop rotation pattern is the process of growing two or more crops on the same piece of land in a planned sequence and according to a definite plan over several seasons in order to avoid the development of diseases and weeds, a decrease in soil fertility and growers' income risk associated with a single crop production. Crop rotation patterns adopted and variations of them are the underlying factors that will influence the decisions relating to area of each crop to irrigate and type of crop to plant including crop mix.

The decision of what area of each crop to irrigate can be influenced by the crop rotation pattern. This is because crop rotation is mainly practiced so that a particular crop having taken various nutrients such as water and fertilisers from the soil is followed during the next growing season by a different crop that returns that nutrient to the soil in order to increase its fertility. This minimises and/or reduces the need and area to irrigate. In this way, crop rotation is considered to have a marked influences over the decision of what area to irrigate on an individual farm.

Crop rotation pattern influences the decision of what type of crop to plant in that some plants follow one another favorably and others don't. Different crops may be planted in a regular sequence so that a crop that leaches the soil of one kind of nutrient is followed during the next growing season by a crop that returns that nutrient to the soil. According to CSIRO (2000) some particular crops are planted immediately post harvest of rice not only to take advantage of the left over soil moisture from the rice crop but also to reduce or even preventing accessions to ground water. The crop planted after rice not only uses water stored in the profile but intercepts winter rainfall that otherwise would have filtered through to the water table. In addition, some plants for instance, have nodules on their roots that contain nitrogen-fixing bacteria. It therefore makes good sense agriculturally to alternate them with other plants that need nitrogen. It also makes good nutritional sense to grow beans and grain at the same time in different fields. In this way, crop rotations influence the type of crop to plant.

What can be said from the above is that crop rotation has the potential to control diseases and weeds, improve soil degradation and prevent the income risk associated with a single crop production. If crop rotation is done properly, growers can keep their fields under continuous production, without a need to let them lie fallow or to apply water and artificial fertilizers, both of which can be expensive.

### 1.1.3 Rainfall

In its simplest sense, rainfall is the total amount of rainwater that falls in drops from vapour condensed in the atmosphere over differing specified temporal periods. Rainfall is the most important climatic factor influencing the crop planting and irrigation behaviour decisions relating to what area and type of crop to plant, timing of crop planting, pre-planting irrigation, area to irrigate, irrigation scheduling and irrigation type a farm will have to establish.

Growers will generally plant crops in areas where they know they will get plenty of rainfall. Where natural rainfall is sufficient to meet plant water requirement during part or all the year, the area planted will be at maximum capacity for a farm. When rainfall is insufficient, then a reduced area will be planted. However it should be noted that in some cases when there is insufficient rainfall, a full area may be planted where it will be possible to provide moisture to the soil by other means say irrigation to support crop growth. Therefore, rainfall determines the crop area adjustment options.

The decisions of what type of crop to plant can be influenced by the amount of rainfall in that some crops grow best in areas and/or field with plenty of rainfall while others prefer dry areas where there is not much rainfall. As previously mentioned, rice crops are grown under ponded conditions, which means that they may be best suited in areas where there is plenty of rainfall (assuming the crops are grown under rain-fed conditions) as compared to cotton crops that prefer hot, dry regions with limited rainfall. In this way, rainfall is considered to heavily influence the type of crop to plant on an individual farm.

Rainfall influences the decisions of when to plant in that planting starts when there is water for crops which is received directly and/or indirectly from rainfall in order to grow. Rainfall also determines the length of the growing season for crops. For example, the timing of opening rainfall in the wheatbelt region is the main determinant of the length of the growing season for crops and pastures (Kingwell et al 1993). The later a crop is sown the shorter the growing season before rainfall ceases and the sooner it experiences unfavourable growing conditions such as shortening day length and low temperatures.

Consequently late-sown crops have a relatively low yield potential and in seasons permitting early sowing, yield potential is high.

Irrigation scheduling is heavily influenced by the amount of rainfall received on the farm. Rainfall water can simulate the impact of a grower's actual irrigation schedule including the ability to suspend irrigation completely. If there is plenty of rainfall, it will provide the crop water requirement and/or the amount of water needed to raise crops and water to meet both consumptive and other needs, such as land preparation, land submergence, leaching and so on. Thus, actual irrigation schedules would not occur and vice verse.

Rainfall occurring prior to planting will effect pre-planting irrigation decision. This is because pre-planting irrigation is the process of using irrigation water to fill the soil profile to field capacity if there has been insufficient rainfall in the time leading up to planting day. Therefore if there had been rainfall occurring prior to planting, pre-planting irrigation can significantly be reduced or even eliminated completely. In other words, if the soil moisture deficit is fairly small as a result of rainfall then pre-planting irrigation would not occur.

Rainfall can also influence the crop production from the start of the first tillage operation until the harvest, water intercepted by the crops, water lost by evaporation from the soil surface, precipitation lost by evapotranspiration during growth, water fraction which contributes to leaching and percolation or facilitates other cultural operations either before or after sowing of crops on the farm. It should be noted however, that rainfall is not always useful or desirable at the time, rate or amount in which it is received. Sometimes it can be destructive and harmful on crop yield and quality and can cause water lodging or crop damage. The Effective rainfall is that quantity of rainwater that is useful or utilisable in raising crops planted on the farm.

### 1.1.4 Temperature

Temperature described in a qualitative manner is that which determines the sensation of warmth or coldness felt from an area over a given time frame, as well as on specific days. Temperature influences the decisions relating to what type of crop to plant, timing of planting, irrigation scheduling and timing and irrigation type a farm has or will have to establish.

Temperature will determine what type of crop to plant on an individual farm. Some crops grow well under high temperatures whereas others don't and instead do better under mild or cool temperatures. For example, cotton originated in hot, dry regions and prefers those conditions to achieve maximum production (Constable 1988) and some annual crops, such as beans and tomatoes are extremely sensitive to light frost and cannot be planted in an area until minimum air temperatures remain above $0^{o}$C (Jensen (1983). These sensitive crops grow only until the first frost in fall. However, other annual crops can survive light freezes in spring and fall. Perennial crops begin growing when the average temperature in the spring reaches and remains above $5^{o}$C and continue growing until the average temperature in the fall drops below $5^{o}$C. Citrus can be grown where only mild freezes occur during the winter months (Jensen 1983). In this way, temperature is considered to have a marked influence over the decision of what type of crop to plant.

For some crops such as cotton, temperature is the dominant factor influencing the timing of planting on an individual farm. This is because the higher the average temperature, the faster cotton will grow and develop, and the longer and hotter the season, the higher the potential yield. The soil temperature determines the earliest date of planting for cotton (Constable 1988). Planting starts when soil minimum temperature at a 10 cm depth exceeds $14^{0}$C for at least three days. In most areas of Australia, the recommended early planting period for cotton crop is late September and/or early October because soil temperature is higher in mid September and falls again in late September or October. This guarantees good seedling vigour, allows maximum time for crop growth and development and ensures maximum yield potential at earliest date. When cotton is planted during cool temperatures and/or seasons, reductions in cotton fibre are more likely to occur (Constable 1988). A reduction in cotton crop fibre diameter indicates poor quality cotton crop. Frost will stop growth of cotton crops or even kill them, so the date of the first frost in autumn determines the end of the season. The cotton seed vessels (bolls) that are not fully developed by this date are unlikely to open for harvest. The date of first frost therefore also determines date for the last effective flower for a given region. Therefore, temperature influences the timing of planting, development and production of reliable cotton yields.

Temperature is recognised as having an important influence over the decision of irrigation scheduling and irrigation type a farm will have to establish in that the temperature or the heat of the surrounding air transfers energy to the crop and exerts such controlling influence on the rate of evapotranspiration. Higher temperatures will result in higher evapotranspiration and greater root exploration and hence the need for higher volume of water and less of the fertilisers to be applied. This in turn will influence what type of irrigation system will have to be installed. Overhead or low-level sprinklers are more likely to be the preferred irrigation type to drip irrigation because sprinklers irrigate at higher volumes than drip systems. In this way, Temperature is said to influence the decision of irrigation scheduling and irrigation type.

### 1.1.5 Crop evapotranspiration

In general, crop evapotranspiration (ET) is the combined water losses from the crops by direct evaporation from the soil and transpiration through the pores (stomata) of the crops. ET is a key climatic factor influencing the decisions relating to irrigation scheduling and timing and type of irrigation system a farm has or will have to establish.

On an individual farm, ET loss is the amount of water compensated for as crop water requirement. In other words the values for ET and crop water requirement are identical and/or same. Thus, irrigation scheduling aiming for maximum yield is determined based on ET values in the field where the soil moisture is maintained at an optimal condition for crop production. Different crops under the same and/or different climatic and agronomic condition in different regions (areas) will require different amount of water needed to meet the water loss through ET. In other words, ET is related to the amount of water needed for crop use and knowledge of ET variation throughout the growing season facilitates irrigation scheduling. In this way, ET is recognised as having an important influence over the decision relating to irrigation scheduling and timing.

ET is recognised as having a marked influence over the decision of what irrigation type a farm will have to install and the systems designs parameters. The design capacity of irrigation systems is based on the peak ET rate and/or irrigation interval (Jensen (1983). Peak ET can determine the size of the channels and watering equipment necessary. Theoretically, the delivery volume of an irrigation system is determined by considering the expected ET rates and area devoted to each type of crops. Therefore, ET is recognised as having an important influence over the decision of what irrigation type to install including the design parameters.

We can be concluded from the above is that knowledge on ET values can help not only in successful application of correct volume of water but also provides the water at the right time. Peak ET rate can help determine the design capacity of irrigation types and/or systems.

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### 1.1.6 Extreme Weather Events

These are loosely defined as extreme weather events such as hurricanes, tropical cyclones, floods, heavy rainfall, droughts, very humid and hot days, fire weather and dust storms. These are considered to have a direct impact on the crop planting and irrigation behaviour decisions in that they lead to a reduction in crop production and increased insurance costs of farm infrastructure.

Passey (2003) conducted a study on "uncertain harvest: the predicted impacts of global warming on Australian agriculture" and found that such extreme events caused severe impacts on crop planting and watering behaviour, and increased uncertainty and risk for agricultural industries. These included:
(1) increased vulnerability to salinity, soil erosion and concomitant nutrient loss.
(2) an impact on water supply infrastructure from increased siltation resulting from episodes of intense soil erosion.
(3) impacts on existing/future water storage design to account for changes in extreme events.
(4) crop damage from heavier rainfall events.
(5) increases in insurance costs associated with increase likelihood of storm damage to public and private infrastructure such as houses and sheds.
(6) implications for emergency planning and evacuation of low lying regions, and the need to alter the design of roads and bridges to cope with enhanced runoff and flood events.
(7) more frequent and extreme bush fires.
(8) severe heat stress for both plants and animals.
(9) significant reduced agricultural yields and even mortality.

Cameron (2000) however proposed the following as the best management practices that can reduce the impact of such extreme weather events:
(1) restructuring the business for lower capital per hectare, splitting nitrogen applications, storing fallow rainfall efficiently and the use of no-till or reduced tillage can improve production during extreme event weather
(2) rotation of crops is the key factor to manage disease, and is the first step to improve yield and water use efficiency
(3) water use efficiency (WUE) is a useful tool for setting yield targets and benchmarking systems
(4) forward selling a crop or using on-farm storage can reduce seasonal price variations
(5) seasonal rainfall forecast help growers refine established management plans by assisting adjustments to nitrogen rates and the mix of crop types
(6) managing soil water is vital to any operation
(7) timing is essential and growers need to be ready to carry out an operation at any time, particularly if farming with a flexible rotation.

What can be said from the above is that government should work together with growers to identify and possibly tackle the root cause of such extreme weather events, especially those which are man-made.

## 1.2 CRITICAL FACTORS REQUIRED FOR SUCCESSFUL WHOLE OF SYSTEM WATER USE EFFICIENCY ASSESSMENT

The following are offered as critical factors that warrant successful whole of system water use efficiency WOS WUE assessment in the Macquarie and Murrumbidgee valleys. The factors are not listed in any particular order and may apply to all regions in Australia. The term "technologies" is used throughout this section to represent all forms of technologies which may assist growers in promoting water use efficiency and making irrigation management decisions.

**Cost of technology** – The technologies and equipments which promote efficient water such as crop water use moisture monitoring tools are expensive. The high cost of these technologies becomes a barrier and makes it unaffordable for growers who cultivate on a small scale in a great majority of irrigation industries in NSW, especially the dairy, grain, lucerne and horticulture industries.

**Technology not proven** – In some cases, growers have not adopted the new technologies that promote efficient water simply because they don't see the benefits and/or need to and they believe that their own judgement is as good as what these technologies will be telling them. Others don't know and/or understand the durability of these technologies and life span of the associated equipment. Therefore, there is a perceived lack of value to the adoption of these technologies in that many growers can't see how they can be more efficient with them. Some growers believe that they have acquired through experience the irrigation management skills that are needed to control crop quality and quantity. This is one of the main reasons why they have never bothered to adapt them. There is also some concern that there are too many technologies to choose from and lack of drive.

**Lack of information** – Some growers seem to have not enough and/or relevant information regarding the technologies which promote efficient water. Growers need more information about these technologies and their impact on the overall benefits. It is felt that research information should be passed on to the grower on the farm. There is a need to improve on the consistency in the information being extended by different agencies.

**Cost of water** – Water is too cheap, certainly water costs are minor compared to other costs and this means that irrigation water in not sufficiently expensive to motivate most growers to improve efficiency. Most growers are unlikely to be able to achieve high water use efficiencies unless they face a pressing need in an increase in water price and to improve in their farming practices.

**Dollar returns and/or gains** – Growers aim at maximising profits from their produces, those who experience lower dollar returns and/or gains and higher production costs are more likely not to spend a dollar on new technologies which promote efficient water use as a means of remaining financially viable and the reverse is true.

**Time consuming** – Growers are experiencing pressure to reduce the time they spend on their farming activities. Some growers have not used the technologies which promote efficient use of water in the past simply because they think the adaptation and adoption is a too much time consuming process. They do not know which technologies would best suit their needs. However, some growers have adopted technologies that improve water use efficiencies such as micro- watering in order to save time irrigating, harvesting and spraying, and to increase their flexibility in the timing of these activities.

**Availability of water** – Although most growers don't experience problems obtaining supplies of irrigation water even when water allocations are below average, water availability and the need to save available water influences the growers incentive to improve water use efficiencies. When available water is limited, the growers need to endeavour to be as efficient as possible and make every drop of irrigation water available contribute towards crop production in order to maximise production from their limited water supplies.

**Poor perceptions and opinions of government policies** – Some growers have misleading perception and opinions about government policies and penalisation of high water use growers is an issue for some growers. However, efficiency in water use is improved by the fear of losing water and/or water licence.

**Life style** – Some growers are not business minded and therefore not driven by economics but lifestyle. There is a needs to understood and addressed this culture and lack of business sense by both improvements on the ground and activities to change attitudes.

**Consultant and extension team** – There is a need to increase consultant and extension services so that a range of views can be exchanged with growers regarding improving water use efficiency and sustainable farming practices. There is concern regarding the impact of staff cut-backs on these teams would have on the growers.

**Age factor** – Age is another factor that comes into play when it comes to water use efficiency improvements. Older growers are less likely to acquire new technologies that improve water use efficiencies compared to the younger ones. The older growers appear to have little interests in these technologies that would requires them to learn new skills, using different machinery etc.

**Technical competence** – Technologies that improve water use efficiencies require higher levels of technical competence. The sophistication of these technologies makes growers in many area prejudiced against efficient water use technologies. Moreover, some special skills and effort are required to cope up with the technologies performance. In fact, these technologies are regarded as complicated methods, which need a considerable level of knowledge and experience. This highlights that education and training is required regarding the use of these technologies.

**Refusal to change practices and farm layout** – Some growers are used to certain farming practices that can be very local and regarded as "good faming" and don't want to change their practice even if there is need to improve water use efficiency. Also, the varied farm layouts and sometimes constrained by the nature of their farm land and physical features such as slope, soil type and soil conditions supports the continuation of what is regarded as "what has worked for the past decades". This in turn results in the growers to use local practices that may not be efficient and/or waste water.

**Lack of exposure** – Some growers and/or communities are in areas that are not recognised as irrigation area. These growers have not yet established themselves with technologies that improve water use efficiency and there is no accountability for their irrigation water use. It is unknown how efficient they can be.

**Record keeping** – It is felt that detailed records on irrigation and crop water use should be kept say in personal diaries or computers. Growers' awareness is that record keeping is becoming more and more important given the possibility of increased water prices and decreased farm allocation.

**Computer literacy** – There is a need for growers to become computer literate so that they can be able to utilise and extract information and data (i.e. weather data) that can be used to help improve water use efficiency from the computer. This will in turn allow for adoption of these technologies and accurate scheduling to significantly improve water use efficiency and thereby improve yields.

**Problems with attaining licences** – There is concern with some growers that the procedures and/or process required to obtain some water licences is complicated and there is need to simplify the process.

We can be said from the above is that a supply push approach (pushing the technology related information at growers to cause rapid adoption) and demand pull (growers transmitting their needs to research workers who respond accordingly) may be desirable to promote the adoption of technologies which improve in water use efficiency that growers do not think they need or do not know about. However, it is important to note that a supply push approach may be appropriate to use with simple water use efficiency technologies. When the technologies are complicated, the more complicated are other factors in the adoption decision and the more complicated are the adoption behaviour of growers.

**Appendix G: Sensitivity analyses of Macquarie Valley Whole-of-System Bayesian Network**

The summary list of sensitivities at the end of the report identifies the findings nodes which will provide the most information about the query node (ie). Detailed information of how each of the 'findings' nodes effect the query node are provided in the first part of this report.

This report shows the sensitivity of the query node (ie) to a finding at the query node itself. Of course, the minimum and maximum beliefs for each state are 0 and 1 respectively, and the maximum reduction in variance is 100%. This node is included in the report for completeness, and to quickly see what the maximum of each sensitivity value is (for example, what the full variance is).

Min and Max are the minimum and maximum values that the query node being tested (ie) can take on for a particular range of values in the finding node.

RMS is the square root of the expected change to the query node (ie) due to the change in the finding node.

Variance is the expected change squared of the beliefs of the query node (ie), taken over all of its states, due to a particular value in the finding node.

Quadratic score is the same as the variance.

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Sensitivity of 'ie' to findings at 'ie':

| Probability ranges: | Min | Current | Max | RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0 | 0.02227 | 1 | 0.1476 |
| 20 to 40 | 0 | 0.02271 | 1 | 0.149 |
| 40 to 60 | 0 | 0.2037 | 1 | 0.4027 |
| 60 to 80 | 0 | 0.2552 | 1 | 0.436 |
| 80 to 100 | 0 | 0.4962 | 1 | 0.5 |
| Change to Mean: | 10 | 73.61 | 90 | 19.58 |

Quadratic scoring = 0.4396

Variance reduction = 383.4 (100 %)

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Sensitivity of 'ie' to findings at 'gw':

| Probability ranges: | Min | Current | Max | RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.01392 | 0.02227 | 0.03467 | 0.0086 |
| 20 to 40 | 0.01403 | 0.02271 | 0.03195 | 0.007549 |
| 40 to 60 | 0.1713 | 0.2037 | 0.2605 | 0.03769 |
| 60 to 80 | 0.2166 | 0.2552 | 0.2983 | 0.03153 |
| 80 to 100 | 0.4069 | 0.4962 | 0.5827 | 0.06512 |

Change to Mean: 69.58 73.61 76.81 | 2.785

Quadratic scoring = 0.002733

Variance reduction = 7.754 (2.02 %)

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Sensitivity of 'ie' to findings at 'eos':

| Probability ranges: | Min | Current | Max | RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.01991 | 0.02227 | 0.02543 | 0.002305 |
| 20 to 40 | 0.02068 | 0.02271 | 0.02584 | 0.001968 |
| 40 to 60 | 0.1836 | 0.2037 | 0.2349 | 0.0201 |
| 60 to 80 | 0.2492 | 0.2552 | 0.2642 | 0.006343 |
| 80 to 100 | 0.4531 | 0.4962 | 0.5267 | 0.02968 |

Change to Mean: 71.96 73.61 74.84 | 1.199

Quadratic scoring = 0.0005294

Variance reduction = 1.437 (0.375 %)

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Sensitivity of 'ie' to findings at 'irr':

| Probability ranges: | Min | Current | Max | RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.02026 | 0.02227 | 0.02508 | 0.002213 |
| 20 to 40 | 0.02069 | 0.02271 | 0.02508 | 0.001771 |
| 40 to 60 | 0.2 | 0.2037 | 0.2113 | 0.004335 |
| 60 to 80 | 0.2506 | 0.2552 | 0.2607 | 0.004293 |
| 80 to 100 | 0.4904 | 0.4962 | 0.4994 | 0.003811 |

Change to Mean: 73.12 73.61 73.89 | 0.3266

Quadratic scoring = 1.593e-005

Variance reduction = 0.1067 (0.0278 %)

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Sensitivity of 'ie' to findings at 'cwr':

| Probability ranges: | Min | Current | Max | RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.02174 | 0.02227 | 0.0228 | 0.000496 |
| 20 to 40 | 0.02235 | 0.02271 | 0.02332 | 0.0004262 |
| 40 to 60 | 0.2023 | 0.2037 | 0.2056 | 0.001342 |
| 60 to 80 | 0.2539 | 0.2552 | 0.2563 | 0.00112 |
| 80 to 100 | 0.4948 | 0.4962 | 0.4973 | 0.001106 |

Change to Mean: 73.49 73.61 73.7 | 0.09282

Quadratic scoring = 1.303e-006

Variance reduction = 0.008616 (0.00225 %)

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Sensitivity of 'ie' to findings at 'dv':

| Probability ranges: | Min | Current | Max | RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.0217 | 0.02227 | 0.02269 | 0.0003987 |
| 20 to 40 | 0.02204 | 0.02271 | 0.02349 | 0.0005631 |
| 40 to 60 | 0.2024 | 0.2037 | 0.2045 | 0.0008715 |
| 60 to 80 | 0.2533 | 0.2552 | 0.2557 | 0.0007267 |
| 80 to 100 | 0.4944 | 0.4962 | 0.498 | 0.001595 |
| Change to Mean: | 73.51 | 73.61 | 73.7 | 0.08367 |

Quadratic scoring = 1.561e-006

Variance reduction = 0.007 (0.00183 %)

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Sensitivity of 'ie' to findings at 'eto':

| Probability ranges: | Min | Current | Max | RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.02203 | 0.02227 | 0.02275 | 0.000238 |
| 20 to 40 | 0.02245 | 0.02271 | 0.02308 | 0.0002125 |
| 40 to 60 | 0.2029 | 0.2037 | 0.2053 | 0.0007902 |
| 60 to 80 | 0.2541 | 0.2552 | 0.2558 | 0.0005646 |
| 80 to 100 | 0.4948 | 0.4962 | 0.497 | 0.0006736 |
| Change to Mean: | 73.5 | 73.61 | 73.66 | 0.05102 |

Quadratic scoring = 4.361e-007

Variance reduction = 0.002603 (0.000679 %)

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Sensitivity of 'ie' to findings at 'dr':

| Probability ranges: | Min | Current | Max | RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.02216 | 0.02227 | 0.02241 | 0.0001199 |
| 20 to 40 | 0.02262 | 0.02271 | 0.02283 | 9.886e-005 |
| 40 to 60 | 0.2032 | 0.2037 | 0.2043 | 0.0004956 |
| 60 to 80 | 0.255 | 0.2552 | 0.2553 | 8.077e-005 |
| 80 to 100 | 0.4954 | 0.4962 | 0.4967 | 0.000633 |
| Change to Mean: | 73.57 | 73.61 | 73.64 | 0.02851 |

Quadratic scoring = 2.51e-007

Variance reduction = 0.0008127  (0.000212 %)

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Sensitivity of 'ie' to findings at 'cpeff':

| Probability ranges: | Min | Current | Max | \| RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.02219 | 0.02227 | 0.02234 | \| 6.219e-005 |
| 20 to 40 | 0.02264 | 0.02271 | 0.0228 | \| 6.993e-005 |
| 40 to 60 | 0.2035 | 0.2037 | 0.2039 | \| 0.0001607 |
| 60 to 80 | 0.255 | 0.2552 | 0.2554 | \| 0.0001484 |
| 80 to 100 | 0.4961 | 0.4962 | 0.4963 | \| 0.0001303 |
| Change to Mean: | 73.6 | 73.61 | 73.62 | \| 0 |

Quadratic scoring  = 1.95e-008

Variance reduction = 0  (0 %)

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Sensitivity of 'ie' to findings at 'gt':

| Probability ranges: | Min | Current | Max | \| RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.02227 | 0.02227 | 0.02227 | \| 6.843e-007 |
| 20 to 40 | 0.02271 | 0.02271 | 0.02272 | \| 7.113e-007 |
| 40 to 60 | 0.2037 | 0.2037 | 0.2037 | \| 1.992e-006 |
| 60 to 80 | 0.2552 | 0.2552 | 0.2552 | \| 1.796e-006 |
| 80 to 100 | 0.4962 | 0.4962 | 0.4962 | \| 1.585e-006 |
| Change to Mean: | 73.6 | 73.61 | 73.61 | \| 0 |

Quadratic scoring  = 2.898e-012

Variance reduction = 0  (0 %)

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Sensitivity of 'ie' to findings at 'cp':

| Probability ranges: | Min | Current | Max | \| RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.02226 | 0.02227 | 0.02228 | \| 9.658e-006 |
| 20 to 40 | 0.02269 | 0.02271 | 0.02273 | \| 1.284e-005 |
| 40 to 60 | 0.2036 | 0.2037 | 0.2037 | \| 2.658e-005 |
| 60 to 80 | 0.2552 | 0.2552 | 0.2552 | \| 2.501e-005 |
| 80 to 100 | 0.4961 | 0.4962 | 0.4962 | \| 2.294e-005 |
| Change to Mean: | 73.6 | 73.61 | 73.61 | \| 0 |

Quadratic scoring  = 5.705e-010

Variance reduction = 0  (0 %)

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Sensitivity of 'ie' to findings at 'twd':

| Probability ranges: | Min | Current | Max | \| RMS Change |
|---|---|---|---|---|
| 0 to 20 | 0.02227 | 0.02227 | 0.0223 | \| 3.675e-006 |
| 20 to 40 | 0.02271 | 0.02271 | 0.02276 | \| 4.896e-006 |
| 40 to 60 | 0.2037 | 0.2037 | 0.2038 | \| 1.177e-005 |
| 60 to 80 | 0.2552 | 0.2552 | 0.2552 | \| 3.305e-006 |
| 80 to 100 | 0.496 | 0.4962 | 0.4962 | \| 1.703e-005 |
| | | | | |
| Change to Mean: | 73.6 | 73.61 | 73.61 | \| 0 |

Quadratic scoring = 1.758e-010

Variance reduction = 0 (0 %)

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Sensitivity of 'ie' due to a finding at another node:

| Node | Variance | Quadratic |
|---|---|---|
| ---- | Reduction | Score |
| ie | 383.4 | 0.4396490 |
| gw | 7.754 | 0.0027334 |
| eos | 1.437 | 0.0005294 |
| irr | 0.1067 | 0.0000159 |
| cwr | 0.008616 | 0.0000013 |
| dv | 0.007 | 0.0000016 |
| eto | 0.002603 | 0.0000004 |
| dr | 0.0008127 | 0.0000003 |
| cpeff | 0 | 0.0000000 |
| gt | 0 | 0.0000000 |
| cp | 0 | 0.0000000 |
| twd | 0 | 0.0000000 |

## GLOSSARY

### Bayesian Networks:

| | |
|---|---|
| Additional impacts | These are factors which are changed as a result of interventions that do not affect anything else in the environmental system. |
| Bayesian Networks | Decision support system (DSS) tools that can be used to help structure decision processes and support analysis of the consequences of possible decision choices by making information and data easily accessible and allowing "what if" analyses. |
| Child node | A node and/or variable that has links feeding into it from the other variables. |
| Conditional probability | The probability of an event occurring given that another event also occurs. It is expressed as P(A/B), which can be read as "Probability of Event A on condition that Event B occurs. |
| Controlling factors | These are factors that cannot be changed by intervening at the scale you are considering but control the environmental system in some way. |
| Divorcing | A technique for simplifying the structure of a Bayesian network by grouping a number of parent variables so that they feed into an extra, intermediate child. |
| Environmental system | A special class of management system relating specifically to environmental system that includes physical, economical, social and institutional factors. |
| Implementation factors | These are factors which directly affect whether the intervention can be successfully implemented both immediately and in the future. |
| Intermediate factors | These are factors which link management objectives and interventions. |
| Interventions | The things that need to be implemented in order to achieve the management objectives. |

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| Management objectives | These are things that need to be affected and/or improved or prevented from worsening through management of water resources. |
| Nodes | The element of a Bayesian network that represents a management system variable being modelled. |
| Parent node | A node and/or variable that has links going out of it to the other variables. |

## Others:

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| Area of crop to plant | The total area of crop that is planted by the grower on a farm. |
| Catchment | A structure in which water is collected. |
| Catchment Unaccounted for Water | The potential water that could be saved at catchment scale. It is the difference between the sum of the volume of input water and the sum of the quantified water outputs (volume of water diverted for irrigation and the end of system flows). |
| Climate | The regular condition of the weather at a place usually over a period of years as exhibited by temperature, wind velocity, and precipitation. |
| Crop planting | The process of sowing with seeds or setting of crops in the ground. |
| Dam | The barrier across a river to hold back water, while a reservoir is the body of water held behind a dam. |
| Decisions | The growers' ability to make clear opinions on farm activities that may involve time and money and act on them. |
| First order decisions | Decisions made on a long-term basis. |
| Influences | The ability to produce an effect on the decisions made by growers. |
| Irrigation scheduling and timing | The decision of determining how much water to apply and deciding when to start and stop watering on the farm. |
| Irrigation type | The irrigation method used to apply water to the crop. |
| Pre-planting irrigation | The decision of irrigating prior to planting or soon after planting of crops, the aim of which is to increase the soil moisture content to assist in seed germination and establishment. |

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| River bed | The area between the banks of a river ordinarily covered by water. |
| Scheme Unaccounted for Water | The potential water that could be saved at scheme level. It is the difference between the volume of water input (rainfall additions plus the volume of water diverted from the river system) and the volume of water delivered to the farms. |
| Second order decisions | Decisions made on a short term basis. This may be daily, weekly, monthly or on a season by season basis. |
| Spatial | Pertaining to or involving or having the nature of space. |
| Temporal | Relating to or limited by time. |
| Timing of crop planting | The time at which the seed was sown and/or crop was set into the ground. |
| Type of crop to plant | The type of crops grown by the grower on a farm. |
| Valley | A long depression in the surface of the land that usually contains a river. |
| WaSim | A computer water Simulation model. |
| Water balance | A method to account for mass based on the law of conservation of mass. |
| Watering Behaviour | The application of water to soils for the purpose of supplying the moisture for either maximum crop production, or in some cases that is essential for crop growth. |
| Watershed | The area that drains to a common waterway, such as a stream, lake, estuary, wetland, or even the ocean. |