IRRIGATION INSIGHTS

NUMBER 5

WATER USE EFFICIENCY

AN INFORMATION PACKAGE

Helen Fairweather, Nick Austin
and Meredith Hope, NSW Agriculture

NATIONAL PROGRAM FOR
Sustainable Irrigation

WATER USE EFFICIENCY

AN INFORMATION PACKAGE

Irrigation Insights Number 5

"It is not the quantity of water applied to a crop, it is the quantity of intelligence applied which determines the result - there is more due to intelligence than water in every case"

ALFRED DEAKIN 1890

Helen Fairweather, Nick Austin and
Meredith Hope, NSW Agriculture

Land & Water AUSTRALIA research • development • innovation

NATIONAL PROGRAM FOR Sustainable Irrigation

ACKNOWLEDGMENTS

The support of NSW Agriculture's clerical officers in compiling the literature and research database, which is a compendium to this document is also acknowledged: Libby Martin, Anmaree Leslie, Jakke Bogie and Kate Scholefield.

The individuals and organisations that provided case studies are gratefully acknowledged.

Thanks to the following reviewers for providing constructive input that has improved the original document:

Steven Raine, National Centre for Engineering in Agriculture, Toowoomba, Queensland
Jim Purcell, Aquatech Consulting Pty Ltd, Narrabri, NSW
Derk Bakker, Agriculture WA, Perth, WA
Mark Skewes, Rural Solutions, Loxton, SA
Gregg Dill, Canada

Most of the photographs included in this publication were supplied by David Williams (Irrigation Officer, NSW Agriculture). Thanks to David for providing these photographs. The graphics provided by NSW Agriculture graphic designer, Nichole Irvine, are also much appreciated.

PUBLISHED BY

Land & Water Australia
GPO Box 2182
Canberra ACT 2601
Phone: 02 6257 3379
Fax: 02 6257 3420
Email: <public@lwa.gov.au>

PUBLICATION DATA
Irrigation Insights No. 5
WATER USE EFFICIENCY, AN INFORMATION PACKAGE

Product No. PR030566
ISBN 1 920860 09 6

Edited by Anne Currey

Designed and desktop published by Graphiti-design, Lismore

Production assistance Joe McKay

CONTENTS

PREFACE

This publication forms part of the National Program for Sustainable Irrigation *Irrigation Insights* series. It explores some of the many facets of the term water use efficiency, and attempts to provide a simple, clear and concise guide to the topic. It also collates and summarises some of the current scientific and field knowledge, though with a rather 'Australia-centric' flavour.

The publication was written to a brief that required the production of a compendium of current knowledge on water use efficiency that:

- provides an explanation of and context for water use efficiency at a range of scales
- reviews and assesses procedures for estimating water use efficiency
- presents case studies and examples of water use efficiency estimation at a range of scales
- reviews the current status of water use efficiency research and development.

It is intended to appeal to a wide audience, from water users, through to academics, service sector, agencies and technocrats and, as such, is a practical, rather than theoretical, guide.

Publication structure

The publication has five chapters that consider water use efficiency at a range of scales, based on the framework that was developed by Barrett Purcell & Associates in 1999. The framework and definitions were developed after an issues paper was circulated and a workshop of key stakeholders was conducted in June 1999.

Chapter 2, "Water Use Efficiency – Terms and Definitions", highlights the important distinction between water use efficiency and performance indices. This chapter also introduces the concept of the water balance, which underpins all water use efficiency definitions. Definitions from the Barrett Purcell & Associates framework include conveyance; distribution; field; and overall project efficiency.

Chapters 3 to 6 consider the practical elements of the water balance:

- Element 1 Storage
- Element 2 Conveyance/distribution
- Element 3 Field
- Element 4 Whole-of-system.

Whole-of-system is not included in the Barrett Purcell & Associates framework but was considered by the authors to be worthy of attention. Within each of these four chapters the current situation; measurement; implementation and adoption; and emerging issues are addressed. Where available, procedures for estimating water use efficiency are reviewed and assessed and case studies at a range of scales presented.

CHAPTER 1

IRRIGATION IN AUSTRALIA

Irrigation plays a vital role in Australian agriculture. In the five years to 2000-01, irrigated agriculture contributed half of the net economic return from all agriculture, from only 0.5% of agricultural land. The gross value from irrigated agriculture for 1996-97 was $7.254 billion.

The impact of irrigated agriculture on water resources is significant. In Australia, irrigated agriculture uses 75% of consumed water. The Australian Water Resources Assessment (2000) estimated that 26% of Australia's river basins and 34% of Australia's groundwater management units are nearing or exceeding sustainable extraction limits. There is increasing competition between users, and growing recognition of the environment as a legitimate 'user' of water. The irrigation industry is facing restrictions, and in some cases reductions, in water availability and entitlements. Future growth in irrigation now depends on efficiency gains in existing enterprises, rather than further use of scarce water resources.

The irrigation sector must be able to use the resources efficiently (with minimal losses and deterioration of quality) and effectively (with maximum productive output). It is these principles, efficiency and effectiveness, that are encompassed by the concept of water use efficiency.

Commonwealth and State governments have identified improving agricultural water use efficiency as a major priority. As a result of national and State water reforms, irrigation water is becoming less available, more tradeable and more expensive. Improvements in water use efficiency at farm level are required, often to simply maintain farm viability. Much effort and investment have been, and continue to be, directed at defining, determining and increasing water use efficiency at field, farm, regional and basin scales.

While awareness of the finite nature of water resources is increasing, detailed data relating to water use are scarce. For example, 31% of Australia's surface water management areas and 30% of groundwater management units have no recorded use data. While the Council of Australian Governments (CoAG) water reforms (described on page 4) and State water legislation recognise the environment as a legitimate user of water, environmental flow requirements cannot yet be clearly defined.

Not surprisingly, the term 'water use efficiency' is increasing in prominence, and is being used to describe a multitude of aspects of irrigation performance. Water use efficiency has no single 'correct' definition but has been used widely and flexibly to describe many aspects of the performance of irrigated agricultural production systems.

On-farm channels

Note. Figures in this chapter are taken from the *National Land and Water Resources Audit, 2001.*

Irrigation trends in Australia

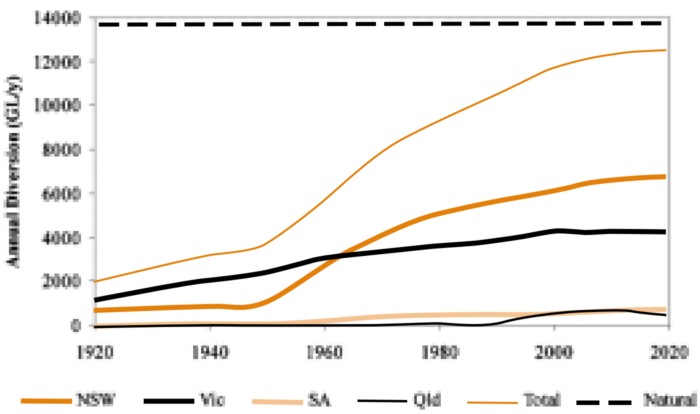
Development phase

Irrigation in Australia started in the early 1800s, mainly through the initiative of individuals who developed water resources to ensure feed for livestock. The first government involvement in irrigation occurred in Tasmania in about 1840. However, it wasn't until the late 1800s that irrigation development began in earnest. The Renmark and Mildura schemes started in 1887, largely as a result of the efforts of the Chaffey brothers and the adoption of irrigation technology from California.

During the 19th Century, droughts and a growing population heightened interest in irrigation, and prompted investment by government, e.g. Burrinjuck Dam was built to supply water to the Murrumbidgee Irrigation Area (MIA). Soldier settlement schemes following the First and Second World wars were financed by both Commonwealth and State governments, and were dependent on intensive farming made possible through irrigation.

Subsequently, the rate of irrigation development grew rapidly, with greatest expansion in the Murray-Darling Basin in southeastern Australia (Figure 1). In the thirteen years between 1983-84 and 1996-97, irrigation water use in Australia grew by 75%.

Figure 1 Growth of irrigation development in the Murray-Darling Basin.



Management phase

In response to growing concerns about the level of irrigation development, the Murray-Darling Basin Ministerial Council[1] initiated an audit of water use in the Murray-Darling Basin in the early 1990s. The audit concluded that growth in water use was unsustainable, and would reduce security for existing users and exacerbate river health problems. In response, the council introduced a Cap on diversions. The Cap is defined as:

> *"The volume of water that would have been diverted under 1993-94 levels of development. In unregulated rivers this Cap may be expressed as an end-of-valley flow regime"* (MDBMC 1995)

The Cap was formally put in place by the Ministerial Council 1 July 1997, and is seen as critical to the long-term health of the basin's rivers. The Cap has resulted in an emphasis on achieving greater efficiency in water use. The Independent Audit Group, established by the Ministerial Council, observed:

> *"The Cap should restrain diversions, not development. With the Cap in place, new developments should be allowed, provided that the water for them is obtained by improving **water use efficiency** or by purchasing water from existing developments."* (IAG 1996)

[1] Ministers responsible for land, water and environmental resources in each of the Commonwealth, New South Wales, South Australia, Victoria and Queensland governments, with power to make decisions for the basin as a whole.

Individual State agencies are responsible for implementing the Cap. In addition to the Cap, states are pursuing their own water reform processes. These reforms, while seen as essential to achieve effective water resource management, have the potential to reduce development below the 1993-94 Cap levels.

In 1994, the CoAG introduced a strategic framework for water reform. The framework of reform aims to improve the efficiency and effectiveness of water service providers and to institute water management planning that takes into account the effect of all water use (by agriculture, industry, households and the environment). Specific areas of reform include:

- water pricing (full cost recovery and transparency of cross-subsidies)
- water allocations or entitlements (separation of water property rights from land, and clear specification of entitlements in terms of ownership, volume, reliability, transferability and, if appropriate, quality)
- provision for the environment as a legitimate user of water
- institutional reform (separation of water resource management and regulation from service provision, and greater responsibility at the local level for the management of water resources)
- water trading
- integrated catchment management and economic viability and ecological sustainability of future investment in irrigation schemes
- greater public education about water use and consultation in the implementation of water reforms
- appropriate research into water use efficiency technologies and related areas.

Well defined and protected water property rights are a prerequisite to achieving the equitable sharing of, and maximising the sustainable benefit from, water resources. Property rights for water relate to ownership tenure, volume allocated, constraints to use or access, constraints to and rules on transferability, and agreed standards of commercial services to be delivered. Progress still needs to be made in adequately defining property rights for both surface water and groundwater.

Evolution of water use efficiency and irrigation performance concepts

Water use efficiency (WUE) concepts have evolved over a century of irrigation development. The following section provides a brief overview in chronological order of the key studies that have influenced the way people think about water use efficiency. See Bos and Wolters (1989), Clemmens and Solomon (1997) and Solomon (1984) for more information on the following definitions.

1920s

- Brown (1920) introduced the term ‘duty of water’ defined as “the measure of the efficient irrigation work that water can perform, expressed in terms establishing the relation between the area of crop brought to maturity and the quantity of water used in its irrigation”.
- Fortier (1928) used the term ‘permissible waste’, and observed that there would always be a limit to improvements that would be governed by economics.

1930s

- Israelsen (1932) defined irrigation efficiency as “the ratio of irrigation water transpired by the crops of an irrigation farm or project during their growth period to the water diverted from a river or other natural source into the farm or project canal or canals during the same period of time.”

1940s

- Christiansen (1942) introduced a uniformity coefficient, which is a ratio of depths that represents the lower proportion of applied depth to the average applied depth across the field.

1960s

- Hansen (1960) used the term water storage efficiency, which is the ratio of water stored in the rootzone during the irrigation, over water required in the rootzone before the irrigation.
- Hall (1960) defined a seasonal application efficiency to extend application efficiency for a single irrigation event to the entire irrigation season.
- The water storage efficiency concept of Hart and Reynolds (1965) was based on the notion of adequate irrigation, i.e. if the amount applied to an area meets or exceeds the irrigation requirement at the time of application.

1970s

- Willardson (1972) outlined the physical (soil infiltration characteristics, stream size, soil volume available for water storage, sprinkler spacing, nozzle size, pressure and wind conditions), economic (water costs, land preparation costs, labour and equipment costs and crop value) and political factors (water laws and geographical location) that affect water application efficiency.
- Merriam and Keller (1978) introduced the concept of application efficiency and distribution uniformity based on the average of the lower quarter of measured applied depths, which was considered to provide both a measure of efficiency and adequacy.

1980s

- Solomon (1984) related irrigation uniformity and efficiency measures to expected yields from uniform irrigation of hypothetical crops. Two of the measures defined are yield-related efficiency measures that assess exactly the usefulness of the water application to the crop and measure the significance of irrigation system and management decisions.
- Whittlesey *et al.* (1986) described adequacy of irrigation as the percentage of the rootzone throughout a field that is restored to field capacity during irrigation. Therefore, obtaining an adequacy level of 100% will result in percolation losses because of the non-uniformity of application.
- Blair and Smerdon (1988) defined a deficit/excess efficiency for use in evaluation of the efficiency of surface irrigation, which combined characteristics of application efficiency, Christiansen's (1942) uniformity coefficient, and storage efficiency.

1990s

- Allocative efficiency, an economic measure that focuses on the adjustment of inputs and outputs to relative prices, was introduced by Omezzine and Zaibet (1998).
- Irrigation sagacity, which is a measure of prudent water use, was recommended by Solomon and Burt (1997). Sagacious uses are defined as being either beneficial, or non-beneficial but reasonable. Non sagacious uses are those without economic, practical or other justification and are considered non-beneficial and unreasonable. Solomon and Burt (1997) list the steps to establish whether a non-beneficial use of water is reasonable. The essential difference between the traditional irrigation efficiency and irrigation sagacity is the inclusion of the non-beneficial, though reasonable use, of water. For example, evaporation from channel, some soil evaporation, and deep percolation due to preferential flow are non-beneficial but reasonable losses.

A prerequisite for estimating any of the efficiencies outlined above at any spatial or temporal scale is the water balance, at that same spatial or temporal scale. This water balance can be classified in terms of its physical location (atmosphere, plant, soil, groundwater, surface water) and in terms of the recoverability of water at any location. A further judgement can then be made on whether the use of the water is reasonable or beneficial or both (Burt *et al.* 1997).

Improving water use efficiency by the irrigation sector

Much has been written about improving water use efficiency. The *National Land and Water Resources Audit (2001)* identifies four priority activities to improve water use efficiency, as shown over page.

The four activities are:

- **full cost pricing**, including environmental cost, as promoted by the National Water Reform Framework
- **implementing water use monitoring** as part of water administration and allocation activities
- **progressively implementing volumetric allocation**, metering, recording systems and reporting (through water supply companies, management authorities and government agencies) at least for highly- and over-committed surface and groundwater systems
- **setting targets for water use efficiency** to reduce water consumption in urban areas and improve water use efficiency in irrigation practice, and undertaking initiatives to meet these targets.

Improving water use efficiency can result from better managing factors such as water application and prevent symptoms of poor irrigation as shown here.

Improving the efficiency and effectiveness of water use can result from better managing a number of factors, including water availability, fertility, pests and diseases, crop or pasture variety, planting date, soil water conditions at planting, plant density and row spacing. This means that improving water use efficiency requires an understanding of the whole system and should not focus solely on the application of water. However, the scope of this publication is confined to the capture, conveyance and application of water for irrigation.

To be able to quantify any improvements in irrigation performance obtained either through better management or through the application of technology, it is important to measure a baseline efficiency. This baseline refers to the performance of the system before improvements are implemented. In addition, an understanding of the expected level of performance in a given environment will provide guidance on gains in efficiency that may be achievable. These measurements rely on the ongoing collection of reliable water balance data.

Scale

The size of water savings achieved as a result of increased efficiency depend on the perspective of the person evaluating the system, the spatial scale in which the investigation is being made and the use that is made of the 'saved' water. "The upper irrigation project's inefficiency is the lower project's water source" (Bouwer *et al.* 1984), and if the water that is saved is consequently used for expansion of upstream irrigated areas, then from the perspective of downstream users there is no identified saving.

This photo shows uneven irrigation which contributes to poor water use efficiency.

Allen and Willardson (1997) observe:

> *"the use of the term 'irrigation efficiency' has caused an absolute dichotomy between the physical situation of the hydrologic system and the public's and government's perception of the physical nature of water management. These incorrect views are so pervasive and strongly held that billions of dollars have been proposed for investment to correct for low irrigation efficiencies with the general public actually believing that their water problems will be solved."*

CHAPTER 2

WATER USE EFFICIENCY – TERMS AND DEFINITIONS

What is water use efficiency?

Water use efficiency is a term commonly used to describe the relationship between water (input) and agriculture product (output). When used in this way the term is, strictly speaking, a water use *index*. Water use efficiency is also often used to express the effectiveness of irrigation water delivery and use.

Barrett Purcell & Associates (1999) correctly point out that efficiency is in fact a dimensionless term obtained by dividing figures with the same units e.g. volume of water used (output) divided by a volume of water supplied (input). Consequently, the tonnes of produce per megalitre of water used is an *index*, not an *efficiency*. This common mis-usage of the term "water use efficiency" has created great confusion.

Adding to this confusion is the distinction between describing the agronomic performance of the crop (crop water use index) and the engineering aspects of the design and management of the system (irrigation index or efficiency).

A crop water use index compares an output from the system, such as yield or economic return, to crop evapotranspiration. In contrast, an irrigation index or efficiency often compares an output, such as yield, economic return or amount of water retained in the rootzone to an input, such as some measure of water applied (see Figure 3, page 10, and Table 1, page 8, for some examples).

To reduce this terminology confusion, Barrett Purcell & Associates have suggested that water use efficiency be used as an umbrella term or as a generic label for a toolbox. Within this toolbox there are two compartments. The first compartment is a framework for the dimensionless efficiency measures, based on the calculation of a water balance, and the second compartment contains a suite of performance indices e.g. tonnes per megalitre or gross margins per megalitre. They state that:

> *"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 toolbox) should be clearly defined with specific units when used."*

Reporting water use efficiency

Describing the crop water use index and the units used to derive it are the most important parts of this toolbox approach. The description of the crop water use index should also include the spatial and time scales that were used to derive the measure.

Water use indices are generally a ratio of an agronomic or economic variable to a volumetric or depth measure of the water applied to the rootzone, transpired by the crop or available to the crop (Table 1). Therefore, the water use index approach generally measures the productivity or profitability of an irrigation enterprise as opposed to the water balance. The time period considered when calculating an agronomic or economic based water use index is generally over a season or year.

Table 1. Common Water Use Indices (WUI) relating to the application of water to a crop [adapted from Barrett Purcell & Associates (1999) and Skewes (1997)].

INDEX		OUTPUT / INPUT	UNITS
Crop water use indices (WUI)			
Crop Economic WUI	=	Gross return / Evapotranspiration	$ / mm
Crop WUI	=	Yield / Evapotranspiration	kg / mm
Irrigation water use indices (WUI)			
Irrigation WUI	=	Yield / Irrigation water applied	kg / ML
Gross Production Economic WUI	=	Gross return / Total water applied	$ / ML
Irrigation Economic WUI	=	Gross return / Irrigation water delivered to the field	$ / ML
Yield per Drainage Volume WUI	=	Crop production / Drainage volume	kg / ML

Comparing water use indices across different industries is difficult as the variables measured are generally not the same. For example, in the dairy industry, Douglass and Poulton (2000) report irrigation performance as a measure of the product (kg milk), divided by the sum of irrigation and effective rainfall. In the cotton industry, water use indices have been reported as the yield of lint (kg) divided by the irrigation water applied (Keefer *et al*. 1985; Yule 1989). While this enables comparison within each industry (if performance based indices reported by others in the same industry agree), it is not possible to compare performance across industries.

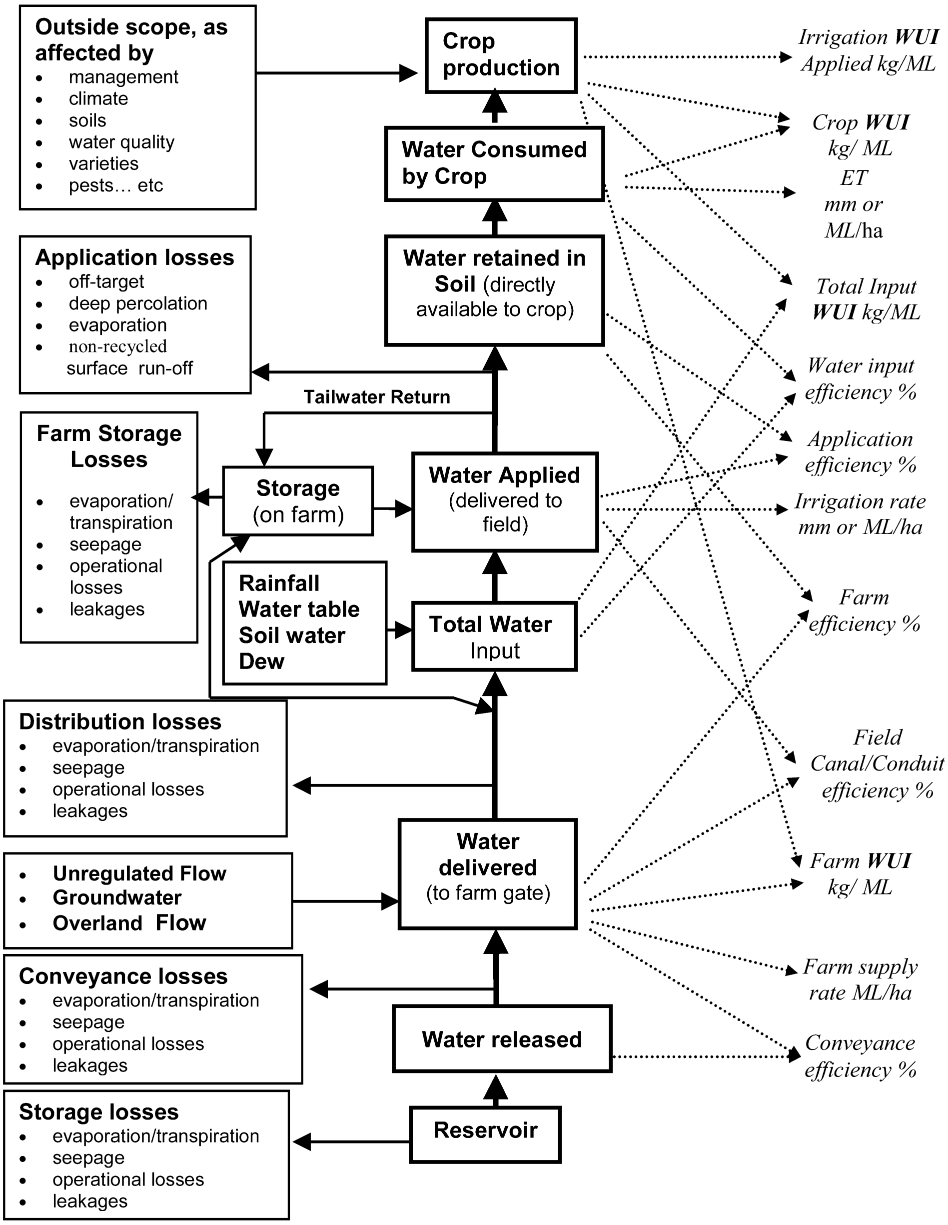
See Appendix for more examples of the water use indices that have been reported for water use efficiency studies across Australia.

The water use efficiency framework

Barrett Purcell & Associates suggested a framework that considers the performance of all aspects of an irrigation system in 1999 (shown in Figure 2, over page). Elements of the framework[1] for water use efficiency are based on a generalised irrigation system. This *Irrigation Insights* is based on this framework and each element is presented in more detail in following chapters.

[1] Another example of a framework is that presented by the International Water Management Institute (Stephens and Hess 1999). The IWMI water balance framework is a reductionist approach in that it only considers the hydrologic part of the irrigation system. This approach is applicable if the losses of the system only come from within, e.g. water loss results from the engineering of channels and structures. However, it has limitations when aspects other than hydrology are considered, e.g. the social system, which includes scheme management and the losses that may be due to untimely releases (Stephens and Hess 1999).

Figure 2. Framework for water use efficiency (adapted from Barrett Purcell & Associates 1999).



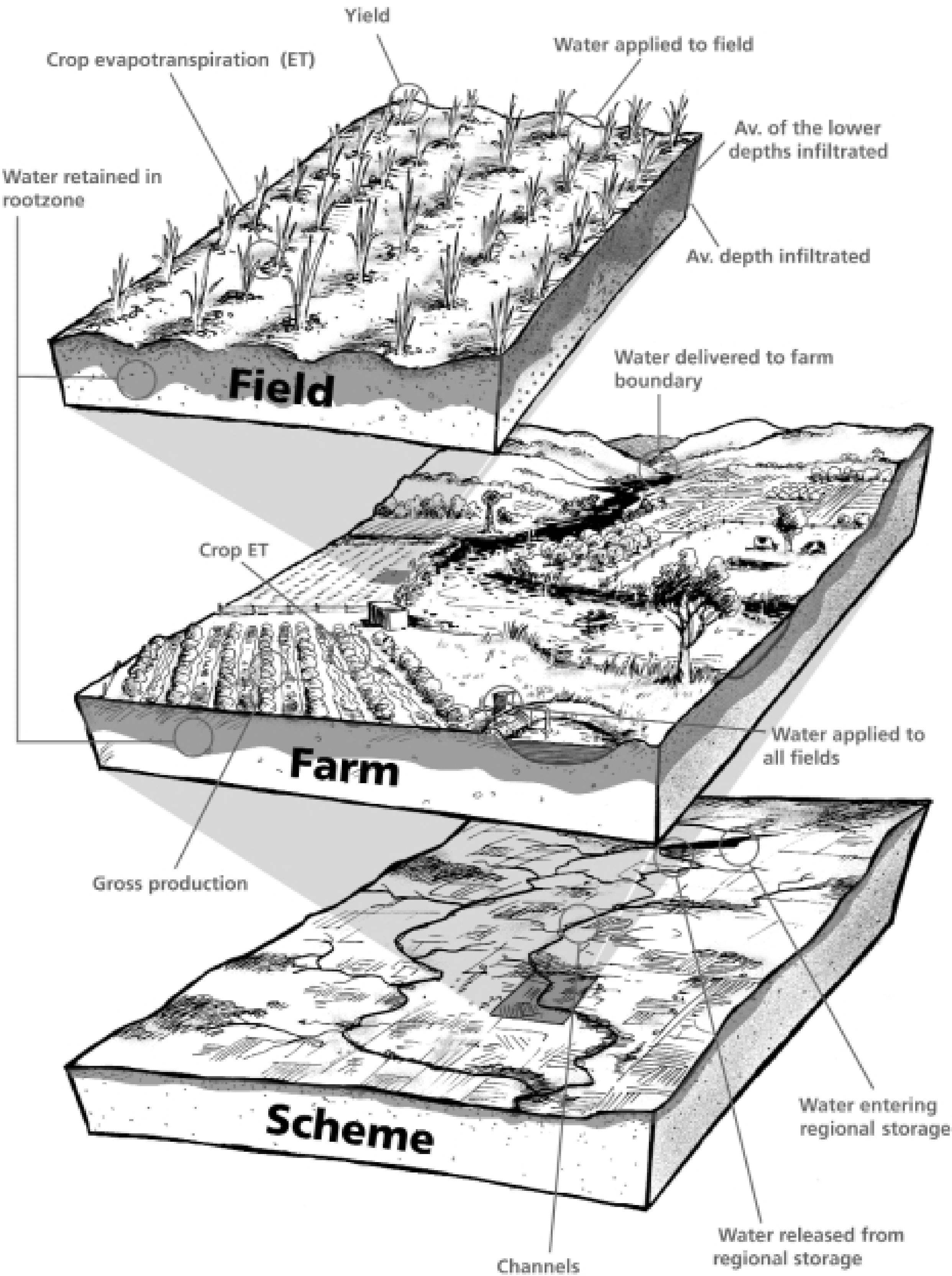
Water balance

There are many irrigation efficiency definitions in the literature most of which share a common element, i.e. is the calculation of a water balance at the appropriate scale.

Water balance calculations require that vertical and horizontal boundaries of the system being investigated be precisely defined. The water balance quantifies the volume of water moving into the defined boundaries of the area under consideration, the change in the volume of water within the boundaries and the volume that moves outside the boundaries. As noted earlier, this *Irrigation Insights* considers the practical elements of the water balance in each of the identified components, as follows:

- storage
- conveyance and distribution
- field
- whole-of-system.

Figure 3. Nested approach for water balance calculations at difference scales.



System level	Crop Water Use Efficiencies and Indices (WUE/WUI)	Irrigation Efficiencies and Indices (WUE/WUI)
Field	Crop WUI = $\frac{Y}{ET_{c(field)}}$	Irrigation WUI = $\frac{Y}{W_{app}}$ Field efficiency = $\frac{W_{rz}}{W_{app}}$ Distribution uniformity = $\frac{d_{lq}}{d_{ave}}$
	Yield (kg) .... Y Water applied to field (mm or ML) .... W_{app} Evapotranspiration (mm) .... ET Av. depth infiltrated (mm) .... d_{ave} Av. of the lower depths infiltrated (mm) .... d_{lq} Water retained in rootzone (mm or ML) .... W_{rz}	
Farm	Crop economic WUI = $\frac{GP}{ET_{c(farm)}}$	On-farm distribution efficiency = $\frac{W_{app\text{-}farm}}{W_{del\text{-}farm}}$ Farm efficiency = $\frac{W_{rz\text{-}farm}}{W_{del\text{-}farm}}$ Farm irrigation WUI = $\frac{GP}{W_{app\text{-}farm}}$
	Evapotranspiration from crops on farm (mm) .... $ET_{c(farm)}$ Water delivered to farm boundary (ML) .... $W_{del\text{-}farm}$ Water applied to all fields (mm or ML) .... $W_{app\text{-}farm}$ Gross production ($) .... GP	
Scheme		Regional storage efficiency = $\frac{\sum W_{del\text{-}farm}}{W_{in\text{-}reg}}$ Conveyance efficiency = $\frac{W_{rel}}{W_{rel}}$
	Channels (ML) Water entering regional storage (ML) .... $W_{in\text{-}reg}$ Water released from regional storage (ML) .... W_{rel}	

Nested efficiencies

Each of the elements fits into one or more spatial and time scales that can help when describing the boundaries of the water balance at field, farm, scheme and catchment levels. Considering each of these scales to be nested in the next larger scale provides a way of understanding the links between each of the scales (see Figure 3). An efficiency measure can be defined at each scale. By careful selection of the terms that are used, the measures from each scale can be multiplied together to obtain an overall efficiency. An overview of these efficiencies and calculations for each of the elements follows.

Field efficiency

Field efficiency can be defined as a ratio of the volume of irrigation water used by the plant to the volume of water delivered to the field. Though this seems straightforward, problems arise when defining the volume of water used for irrigation. Bos (1985) suggests it includes only the water used to produce the extra yield above rainfed production and is therefore described by the net evapotranspiration difference between rainfed and irrigated crops. Similarly, some suggest it includes all the water used by the crop minus the effective rainfall (Burt *et al.* 1997) while others suggest that all water which is used beneficially should be included in the calculations (Heermann *et al.* 1990). Beneficial use is described as being for multiple purposes, including crop water use, salt-leaching, frost protection, crop cooling, and pesticide or fertiliser applications.

Barrett Purcell & Associates consider that even though leaching is recognised as a beneficial use of irrigation water it should be considered as a loss. Therefore, in the context of their framework, an irrigation enterprise that requires leaching of the soil will be less efficient than one that does not.

At the field level the calculations become more complicated as different timescales are considered. The timeframe ranges from a single irrigation (application efficiency) to irrigation over a season (irrigation efficiency). Generally some measure of water used for crop production or applied to the rootzone is compared to a measure of water delivered to the field (see Figure 3).

The water balance elements that are needed to calculate the field efficiency measure depends on the context of the study and the time scale being considered. For example, to calculate the application efficiency of a single irrigation, effective rainfall generally would not be considered. When calculating the field efficiency over an irrigation season, however, the timing of each irrigation will be influenced by the effective rainfall so this could be considered in the calculations. Another complicating factor is rain falling after a well-timed irrigation event. The important consideration is to clearly define the dimensions of the water balance for the irrigation event or season and the field or irrigated area used to calculate the field efficiency.

For more information on field efficiencies see Chapter 5.

On-farm distribution efficiency

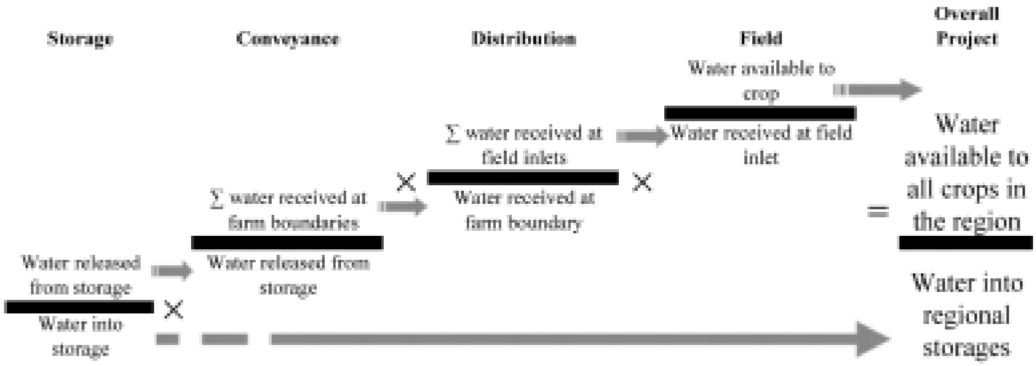
Distribution efficiency refers to the on-farm system used to store and distribute water to the various fields. The timeframe for calculating the water balance of the distribution system can range from a single water delivery to the water delivered over a season or year. A common ratio used to calculate distribution efficiency is the volume of water applied to all fields as a proportion of the volume of water supplied to the farm boundary (see Figure 3).

The spatial boundary of the distribution scheme includes the extent of on-farm storages, channels and pipelines. Therefore, evaporative and seepage losses from storages and channels need to be quantified to measure distribution efficiency. Other factors that need to be considered when calculating on-farm distribution efficiency include operating losses and recycling of runoff.

For more information about on-farm distribution efficiency see Chapter 4.

Figure 4. Nested irrigation efficiency measures (all volumes in ML).

Equation 1



Regional conveyance efficiency

The water balance used to calculate the efficiency of the conveyance system is similar to that used to calculate the distribution efficiency, except that channels, pipes and rivers within the scheme define the boundaries. The conveyance efficiency is a measure of the performance of the water provider in delivering water to the farm where it is required to be applied. The time-frame for assessing conveyance efficiencies can range from a period of days (e.g. when evaluating seepage losses) to an annual or seasonal water balance (e.g. when assessing the performance of the water provider).

For more information about distribution and conveyance efficiencies see Chapter 4.

Regional storage efficiency

To be consistent with the Barrett, Purcell & Associates framework, regional storage efficiency is treated as a separate entity in this publication. Regional storage efficiency is an assessment of the management of water stored for irrigation purposes.

For more information about storage efficiency see Chapter 3.

Overall project efficiency

The overall project efficiency, as adapted from the framework of Barrett, Purcell & Associates, is a product of the storage, conveyance, distribution and field application efficiencies (Equation 1 in Figure 4). On-farm storage can be considered to be an extension of the on-farm distribution system, so it can be included in the distribution efficiency definition (Figure 4 and Equation 1).   On-farm storage efficiency could also be treated as a separate term, if required, to simplify the calculations.

Whole-of-system water use efficiency

A whole-of-system water balance enables the size and location of losses across a landscape to be estimated. These 'losses' can be prioritised in a number of ways, as follows:

- the size of the volumetric or crop loss
- the benefits of reducing loss, i.e. the financial gains
- the financial cost of reducing the loss
- the capacity or resources required to stop the loss.

As noted previously, a whole-of-system water use efficiency is not considered within the Barrett, Purcell & Associates framework. The difficulty in using the project efficiency product outlined in this framework is that an inefficiency or loss at one scale may not necessarily be a loss to the entire system. A whole-of-system water balance aims to account for water across a whole catchment. To do this, the following data are required:

- the physical geography and geology of a catchment or system
- the links between different spatial and time scales. A loss at one scale (e.g. water lost from scheme supply channels) may be a gain in another (farm using groundwater from within that scheme)
- infrastructure such as dams, weirs, off-take points, on-farm storages, type of irrigation system and irrigation fields
- irrigation information such as water used, area irrigated and crops grown
- climatic information such as seasonality of rainfall and evaporation.

For more information on whole-of-system water use efficiency see Chapter 6.

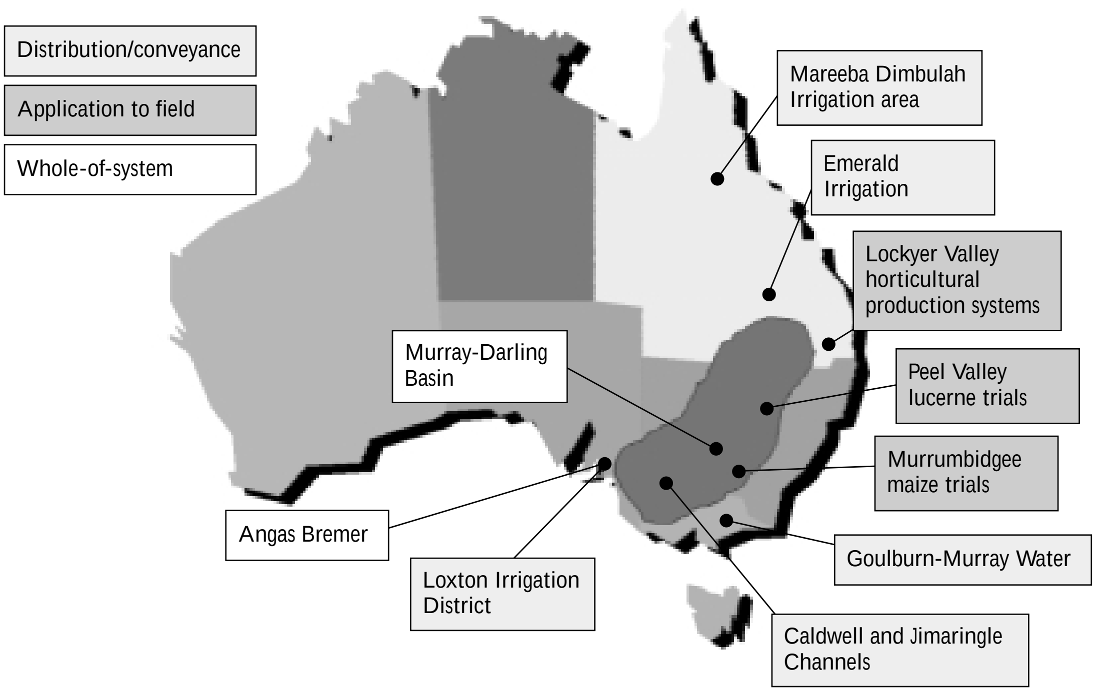
State of research into water use efficiency in the irrigation sector

Research into water use efficiency in irrigation covers all the elements listed previously (storage, conveyance, distribution and field). This research considers the volumetric water balance of each of these elements (conveyance, distribution and irrigation efficiencies), as well as the crop response to water application (water use index). As part of this consultancy a database of current research was compiled and is available from the Land & Water Australia website, www.lwa.gov.au. A summary of the current water use efficiency research projects being conducted in Australia is included in the Appendix.

Case studies

In the following chapters case studies from around Australia are presented to demonstrate the current focus on improving water use efficiency throughout the irrigation industry (Figure 5).

Figure 5. Location of case studies.



CHAPTER 3

STORAGES

Current understanding

Off-farm storages are an important part of an irrigation system, and the building of large dams was the focus of the development of irrigation schemes in Australia between the 1930s and 1990s.

At the start of the 20th Century the combined storage capacity of all large dams in Australia was 250 GL. This storage capacity had increased to 9,540 GL by 1950 and by 1990 it was estimated that the four hundred and forty seven large dams in Australia had a combined storage capacity of 79,000 GL. These dams store water for urban, irrigation and hydroelectric power generation, with irrigation using about 70%, or 55,000 GL, of this stored water.

In recent years there has been a shift in emphasis from building large storages to better managing existing structures and improving efficiency. Thermal pollution, loss of fish and wildlife habitat, dryland and river salinisation, silting of dams, erosion and loss of wetlands are some of the forms of environmental degradation blamed in part on the construction of storages for irrigation.

Because of the variability of flow in Australian rivers, storages have tended to be designed to accommodate larger volumes so that excess flows can be carried over to dry times. These larger storage volumes can potentially contribute to greater losses.

In Australia, the water reform process has restricted, and is continuing to restrict, the amount of water that can be extracted from rivers and storage systems, particularly at low flows. Because of this, the current focus is on developing on-farm water storages to meet irrigators' need for a reliable water supply. The ability to store water on-farm can provide more flexibility in the management of an irrigation system, which can lead to savings in the amount of water applied because applications can be timed to meet crop needs. However, these savings need to be offset by the losses associated with the storage of water.

In 1990 it was estimated that on-farm dams had the capacity to store 9% of the total water stored in Australia (Australian Water Resources Assessment 2000). On-farm dams are smaller than major water storages, but they are also susceptible to losses.

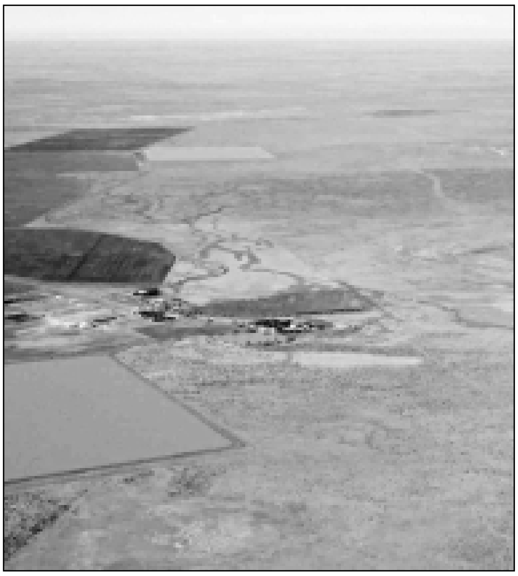
Losses occur from storages through evaporation from the surface, seepage through the base and sides, inaccessible storage volumes due to elevated off-take points and storage failures. Given the generally large storage volumes in Australia, quantifying losses is an important first step in analysing where water savings can be made.

Evaporation from storages can be significant, and a recent focus has been the practicality and potential for controlling these losses, particularly from on-farm storages. The current belief is that there are measures available for controlling evaporation, but they are not cost effective at the present time. Until the technology becomes available at a price that is cost effective uptake is likely to be minimal.

The current focus is on developing covers to shade the water surface, and reducing the area of water for a given volume. The covers being suggested include crystalline solid and various other floating materials (see page 19). The surface area can be reduced by increasing the depth of storage but the economic costs and benefits are likely to vary greatly.

A split cell design is another method of reducing the area for any given volume. In this design, two or more cells are incorporated into the storage, each with a different capacity. All the cells can be used at the same time but when the volume is reduced more water can be stored in a smaller cell. Because of the reduced surface area the evaporative losses are reduced.

While there are some similarities between measuring and decreasing seepage losses from both storages and channels, the major difference between the two systems is that there is non-flowing water in the storage compared with flowing water in a channel. This flow of water requires some extra considerations (see Chapter 4 for more detail on losses).



On-farm storage has become more important as a result of restrictions on the amount of water that can be extracted from rivers and storage systems, particularly at low flows.

Evaporative losses

Water is mainly lost from storages through evaporation. Apart from a water source, evaporation requires an energy source, which is largely provided by sunlight, as well as a transport mechanism for water vapour. The transport mechanism is related to wind speed and humidity.

The combination of energy and aerodynamic factors is often termed the 'atmospheric demand'. In 1948 Penman proposed a 'combination' equation to describe evaporation from a free water body. However, Penman's combination equation assumed a continuous body of open water. In reality, storages are not continuous, and the surrounding land and air have a big impact on evaporation. As comparatively warm, dry air that surrounds storages passes above the storage, it cools and releases energy through advection (the horizontal movement of air). This effectively increases the energy available for, and consequently the total amount of, evaporation, typically by 150 to 200%.

Shading the water storage with a cover or vegetation will inhibit the energy source contributing to evaporation (sunlight). This cover or vegetation will also reduce the transport mechanism by reducing the wind speed and the advection process will be inhibited. Reducing the surface-area-to-volume ratio of the storage by increasing the depth of storage will also reduce evaporation.

The scale of evaporative losses depends on the climatic zone in which the storage is constructed, the mitigating measures implemented and the surface-area-to-volume ratio of the storage design.

Seepage losses

All soils are permeable so all earthen storages or dams leak. How much they leak depends on the soil type, or more specifically, the soil's hydraulic conductivity. Including compacted clay layers will decrease the hydraulic conductivity and therefore seepage losses from storages.

Water can be lost through the walls and bottom of the storage and the main pathway of the water can range from the horizontal to the vertical, depending on local geology, soil type and depth to groundwater. Precipitation of fine clay materials, which results in a buildup of silt at the bottom of the storage, can reduce seepage losses over time. In contrast, seepage losses can increase in time because of the development of leakage pathways through biological means (yabby holes) or physical means (cracks from drying and wetting cycles and cleaning).

The filling and drying cycle can also exacerbate overall seepage losses from a storage. If a storage is allowed to dry out then the impermeable layer can be compromised (through the development of cracks) and the soil beneath the dam can dry out. When the storage is refilled this soil will again absorb moisture to the extent that the filling losses can be considerable.

Seepage losses can be decreased by using high clay content materials to line the storage; these materials should be compacted by applying pressure to the clay material at an optimum moisture content, outlined in various standards (AS1289 2000). Other techniques for decreasing seepage losses include a cut-off trench, which is dug at least 500 mm into the impervious material at the base of the bank.

Measurement

Estimating storage efficiency

Calculating the water balance is the key to estimating storage efficiency. Of all the components in the irrigation system, the water balance of the storage is probably easiest to define as the boundaries of the storage are the same as the boundary of the water balance. The required elements for the water balance are:

- the water into the storage
- change of volume in the storage
- water released from the storage.

The volume leaving the storage comprises the volume that is released as a supply and the volume that leaves the storage as an overflow. This overflow volume is a loss to the system and can be a result of the capacity of the storage being exceeded or untimely releases.

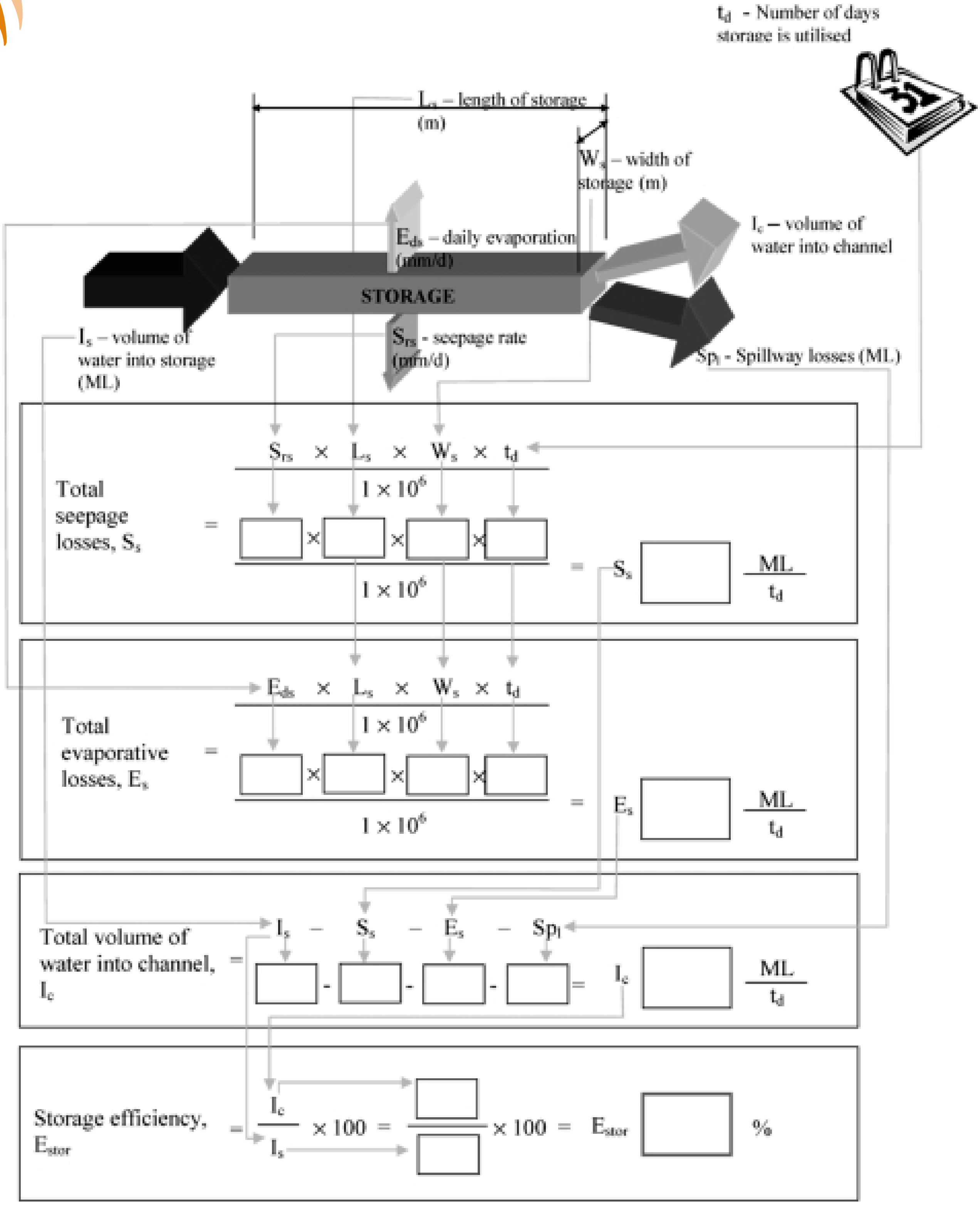
To accurately measure evaporative and seepage losses separately is a difficult, time consuming task, which sometimes needs expensive equipment. However, by installing a simple depth gauge and measuring the other elements of the volume balance (rainfall, inflows and outflows) the combined evaporative and seepage losses can be estimated. A rating curve of depth *versus* volume in storage can be constructed to convert the depth measurements to a volume of water.

Once all the inputs and outputs are known or estimated, the water balance provides the necessary information to calculate storage efficiency. An example of separate seepage and evaporative measurements, assuming an empty storage at the start of the period considered, is shown in Figure 6, over page. Evaporation can be measured using an evaporation monitoring pan and multiplying the measured loss from this pan by a coefficient. The most common method is to estimate the evaporation from the storage as being 80% of the evaporation from a U.S. Class A pan (see Raine 1999 for further details).

There are several ways of estimating seepage rates from channels and storages but most require a lot of resources. However, a simple estimate can be made based on the type of soil used in building the storage. The condition of the storage may require these seepage rate estimates to be revised, e.g. cracks in the storage will create a preferential pathway and increase the seepage rate.

Dalton *et al.* (2001) found that seepage and evaporation losses from on-farm storages in the Border Rivers catchment accounted for 2 to 10% and 14 to 40% of the storage water balance, respectively. The efficiency of these storages ranged from 50 to 85%. The storage with the

Figure 6. Template for calculating storage efficiency when evaporation and seepage are measured or estimated



highest efficiency stored water for the shortest time and therefore the opportunity time for evaporation and seepage was reduced.

The Murray Land and Water Management districts require that storages be built so that seepage is less than 1 mm/d. There were no other studies found that measured seepage rates from storages in Australia. Some estimates of seepage rates from channels are included in the next chapter (see Table 3, page 26).

Techniques and commercial products for reducing losses

Using insoluble monolayers to slow the evaporation of water is being investigated by the University of Queensland. A monolayer is a one molecule thick film (~2 nanometers) that has hydrophilic (water attracting) and hydrophobic (water repellent) parts. Crystalline solid monolayers are thought to be able to reduce the rate of evaporation from a water source on which they are spread.

Aquacaps® are being developed by Royal Melbourne Institute of Technology, Land & Water Australia and Sainty and Associates to suppress evaporation from small water storages. Aquacaps reduce evaporation by providing a barrier on the water surface. The barrier is formed by a free standing floating module, which consists of a dome supported by a ring that penetrates into the water. The cost of installing the Aquacap technology is around $16/m^2$ (2002), which is prohibitive, except for very high value water. To be used in irrigation storages the cost will need to be reduced by at least a factor of 10.

E-VapCap® is a patented system of evaporation control developed by Evaporation Control Systems Pty Ltd. The system is based around a floating cover made from light-impervious polyethylene sheeting that the manufacturers claim will effectively stop evaporation from large water storages. The cost of the E-VapCap is around $4/m^2$, however, winds have been found to be a problem with this system and research is being conducted to improve the performance of the technology in windy situations.

Other floating materials have been used to mitigate evaporation losses with varying results (see Table 2).

Table 2. Suspended materials for evaporative control (Raine 1999).

MATERIAL	EVAPORATION REDUCTION (%)
Lily pads	16
Polystyrene beads	39
Wax blocks	64
White butyl rubber	77
White plastic spheres	78
Continuous wax	87
Suspended plastic sheeting	90
Foam rubber	90
Polystyrene rafts	95

Implementation and adoption

Measuring the effectiveness of storing water for irrigation has not been the focus of many studies in Australia. The need to implement techniques to measure storage efficiency will depend on the capacity of the structure, the environmental degradation caused by poor design and mismanagement of the storage, and the value of the crops being irrigated.

Storage efficiency calculations rely on all the elements of the water balance being measured. Meters are needed to measure storage inflows and outflows. Rain gauges and methods of measuring evaporative and seepage losses are also needed to complete the water balance.

Methods to determine if a storage is leaking include installing piezometers to measure the local watertable depth, Electromagnetic Survey (EMS) and satellite imagery techniques. Methods to reduce losses from storages are similar to those used in conveyance and distribution systems and will be expanded on in Chapter 4.

Emerging issues

The development of localised watertables has been attributed to seepage losses from storages. This has become an issue recently, particularly in the northern Murray-Darling Basin, and can result in a localised salinity problem when the watertable nears the surface.

There is great interest in evaporation control with current projects being conducted by the National Centre for Engineering in Agriculture (see Appendix) investigating the feasibility of covers and surface barriers. There is also a major focus in Queensland on evaluating regional and on-farm storage performance and prioritising redevelopment works.

Current attention is focused on using subterranean dams; storing freshwater underground in existing aquifers in the rainy season and pumping it out in the dry season. These measures will eliminate evaporation losses associated with surface storage, but pumping costs must be analysed to determine its effectiveness. The use of aquifer storage and recovery is limited by the availability of suitable aquifers, and water quality also needs to be considered.

For more information about on-farm storages, see *Controlling Evaporation Losses from On-Farm Storages: Draft Framework* (2003), published by Land & Water Australia.

CHAPTER 4

CONVEYANCE AND DISTRIBUTION SYSTEMS

Current understanding

In the Barrett & Purcell framework, conveyance and distribution efficiencies are two separate entities. They are combined in this document, as the calculation of the water balance required for assessing efficiencies is similar for both conveyance and distribution.

Conveyance losses are defined as those that occur from the time water is released from the reservoir to when it is delivered to the farm gate. It includes evaporation, transpiration, seepage losses and other leakages such as filling losses.

Distribution system losses are confined to those losses occurring from the time water enters the farm boundary until it is applied to the field. This means that it can include on-farm storage losses.

Supply channels are sources of conveyance losses.

According to Howell (2001), there are four basic losses that can result when water is diverted for irrigation, as follows:

1. Part of the water is consumed in evaporation (e.g. from channels) and transpiration (e.g. vegetation growing next to the channel).
2. Some water percolates to surface or subsurface areas (e.g. canal seepage or deep percolation) and cannot be recaptured (e.g. in the vadose zone, the ocean, or a salt sink) or can be recaptured (e.g. interceptor drains into a drainage canal or a drainage well) and used as an additional supply.
3. The drainage water becomes polluted with salts or chemicals (e.g. nutrients or pesticides) that are so concentrated that the water can no longer be used and must be discharged to a sink for disposal.
4. Untimely deliveries of water that cannot be used.

Quantifying these losses is the first step in determining the efficiencies of conveyance and distribution systems. However, they are not the only elements that should be considered. The concepts of adequacy, equity, reliability and consistency are important considerations in evaluating a delivery system.

The elements of the water balance that are usually measured in evaluating a delivery system include discharge or pressure at various delivery points within the system, duration of a delivery, timeliness of the delivery, total volume of water supplied and how often water is delivered at a given off-take. When combined, these measures provide information on the adequacy, equity, reliability and consistency of the delivery system.

The efficiency of a distribution or conveyance system is not necessarily correlated with the technology applied to the system. For example, a simple fixed structure requires less skill to operate than structures that allow variable flow. Therefore, if the operators of the variable flow structures are not appropriately skilled, incorrectly operating the more complicated structures will lead to inefficiencies. Maintenance requirements imposed by the level of technology applied to the conveyance system will also affect the efficiency measures; an unreliable system is an inefficient system.

A highly efficient conveyance system doesn't necessarily result in a highly efficient irrigation system. If water is supplied with very little loss in the conveyance system, but the timing of delivery is such that very little use can be made of the water at the farm level, then the overall performance of the conveyance system can be very inefficient in terms of its reliability and consistency. The following studies illustrate how this can happen.

Krinner *et al.* (1994) found in a study of conveyance efficiency in Spanish irrigation systems that about 10% of the volume of water released at the headworks was lost in conveyance. Evaporation from the water surface of the channels was predicted to be between 0.2 and 1.1% of the volume released, therefore most of the conveyance losses were attributed to seepage and suboptimal management.

In an investigation of an irrigation project in Portugal, Rijo and Pereira (1987) found that conveyance efficiencies were higher during work days compared with weekends and at night. This reinforces the influence of the management aspects of the system on the achievable efficiencies.

Clemmens and Dedrick (1984) monitored a number of delivery sites within an irrigation district to determine the variability of flow rate during water delivery. The variation in the flow rate was found to be a function of the location of the site within the delivery system and did not appear to be affected by time of year or crop type. This variation is indicative of an inequitable and inconsistent system.

The importance of considering the impact of improved conveyance efficiencies on the whole system is highlighted by Moustafa *et al.* (1996). In this study it was concluded that improvements to an irrigation delivery system in Egypt resulted in saved water and improved crop yields. However, the quantity of the drainage water was estimated to have been reduced by 7% with a much lower quality, causing negative effects to the approximately 11% of the farmers on cultivated lands that previously irrigated from the perimeter drains of the irrigation system investigated.

The Queensland Rural Water Use Efficiency (RWUE) Initiative funded several efficiency evaluations of the (then) State Water Projects Water Distribution Systems. The evaluations were conducted by Gutteridge Haskins & Davey Pty Ltd and published in 2001. (Note that State Water Projects is now a corporate entity under the name SunWater.) These publications are available on-line from:

http://www.nrm.qld.gov.au/rwue/publications.html#SWP

In these studies a water balance analysis of the system was used to derive an operational and theoretical[†] water distribution efficiency to enable consistent comparisons across the different providers. The operational efficiency (E_{oper}) is defined as the actual efficiency, which takes into account both uncontrolled losses (evaporation, seepage and local runoff) and operational losses (un-metered use, overflows and other releases) (Equation 2). Only uncontrolled losses are included in the theoretical efficiency (E_{theor}) term (Equation 2).

Equation 1

$$E_{oper} = \frac{\sum \text{(metered use)}}{\sum \text{(water available)}}$$

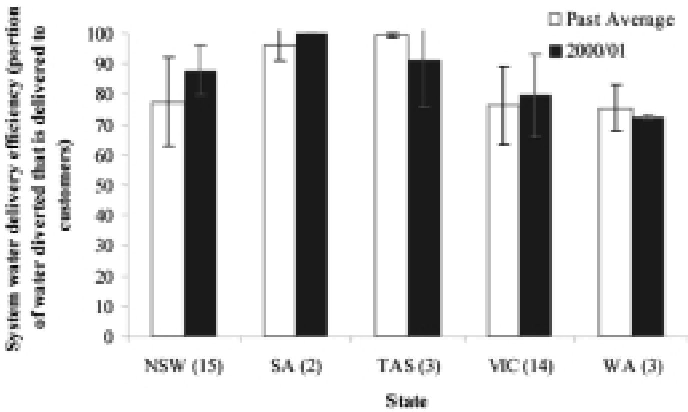
Equation 2

$$E_{theor} = \frac{\sum \text{(metered use)} - \sum \text{(uncontrolled losses)}}{\sum \text{(water available)}}$$

[†]The concept of "theoretical efficiency" was developed to provide an indication of the potential or maximum efficiency of a particular system (Gutteridge Haskins & Davey Pty Ltd 2001).

In 1998, the Australian National Committee on Irrigation and Drainage (ANCID) initiated a project to benchmark Australia's irrigation water providers. This project has collected data and reported on a range of indicators relevant to the key business areas of Australia's irrigation water providers. In the initial report, fifteen indicators were reported and this has grown to sixty five in the latest report, released in 2002. The system water delivery efficiency (portion of water diverted that is delivered to customers) ranged from 45 to close to 100% for 2000-01, however, there is much variation both within and across states, as shown in Figure 7.

Figure 7. Summary statistics of water provider delivery efficiencies (portion of water diverted that is delivered to customers) for five Australian states (ANCID 2002) (number in brackets on x-axis indicates the number of providers in the sample, error bands are +/- 1 standard deviation).

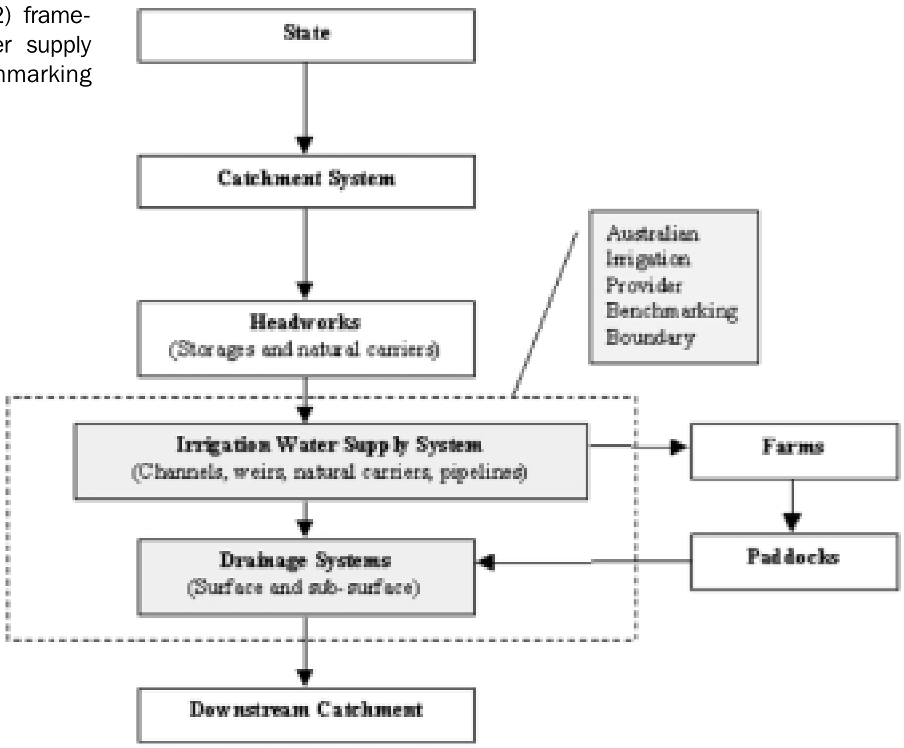


The indicators used by ANCID to benchmark the operational performance of Australia's water providers in 2002 were as follows:

- volume of water delivered
- basis of delivery in terms of total entitlements and resources available
- water delivery efficiency
- extent of volumetric metering of customer water supplies
- extent of water trading between different users.

To benchmark Australian irrigation water providers, the spatial boundary around the irrigation supply system and the drainage system, which included surface and subsurface drainage was defined (Figure 8).

Figure 8. ANCID (2002) framework of irrigation water supply businesses - benchmarking boundary.



ANCID also recognised that irrigation water providers have a major influence on the sustainability of natural resources across significant parts of Australia, even though only 1,363 people are employed in delivering water to irrigators. This is not to discount the impact of water use practices on-farm and it is recognised that water providers may be capable of influencing water use practice at the farm scale.

Channel seepage is the focus of a three-stage project being conducted by ANCID. The first stage of the project, which is currently underway, aims to investigate best practice in channel sealing, and develop easy-to-use standards to identify, measure and quantify channel seepage. The second stage of the project aims to provide best practice procedures and processes for remedial work to seal leaking channels, and the third stage is the development of decision support systems to evaluate the cost effectiveness of undertaking remedial work on leaking channels (see http://www.ancid.org.au for more information).

Measurement

Estimating conveyance and distribution efficiency

Calculating a system water balance is the first step to measure the efficiency with which water is conveyed and distributed to, and within, a farm. Four dimensions need to be considered to calculate a water balance for an irrigation scheme; three spatial and one temporal.

The complexities of calculating a water balance within the constraints of the three spatial dimensions are large enough that in most cases the time dimension is removed by considering the balance over one period only or averaging the water balance over several periods. Therefore, defining this time period is an important component of the water balance and of the efficiency measures that follow from that balance.

The efficiency measure, by definition, requires the losses in the system to be identified. This step is the 'tricky' bit. The size of the losses will change with the boundary constraints that are arbitrarily placed on the system to calculate the water balance.

Consider a conveyance system for a surface irrigation scheme, which supplies water to farmers through a system of constructed open channels. The inputs into this system are the supply from the storage plus any rain that may fall from the time it is released until it is delivered to the farm (usually ignored as it is assumed to be negligible).

The outputs from a conveyance system are the amount of water that flows through the farmers' boundary plus all the 'losses' that occur *en route*. These losses would typically be defined as follows:

- operational
- evaporative
- channel seepage (relatively constant movement of water through bottom and sides of channel)
- leakage (abnormally large escape of water through cracks and fissures).

However, beneficial use of the seepage and leakage losses could be obtained by the farmers who were the original targets of the volume of water sent down the channel. Therefore, if the beneficial use of this 'lost' water is not accounted for, the reported efficiency may be much less than actual efficiency.

Even if the beneficial use of the water is outside of the farmers targeted for the original volume of water, a case can still be made that the water is not 'lost'. This is particularly true of conjunctive use areas, e.g. the Burdekin-Delta area in Queensland, where the source of the irrigation water is both the surface water scheme and groundwater. Therefore, the subsequent beneficial use of 'lost' water should be considered in any assessment of the efficiency of a conveyance or distribution system.

Leeking channels have been identified as an important source of water loss from a conveyance or distribution system.

The water surface, channel bottom and all diversions (including spills and discharge points) are examples of upper, lower and horizontal boundaries, respectively, of a conveyance system. Using these boundaries would result in the calculation of efficiency using a very narrow focus where the aim may be to determine how to modernise a delivery system.

After identifying the spatial boundaries of the conveyance and delivery system and the timeframe for the evaluation the next consideration should be the accuracy of the measurements and the confidence that can be placed in them. Some statistical measure that reflects the accuracy and variation associated with the losses should be reported along with the water balance measurements.

One statistical approach to quantifying the errors associated with the water balance measurements of a conveyance and delivery system is to obtain a frequency distribution of the ratio of the actual flow at each outlet to the intended flow at each outlet. This distribution can be characterised by its mean and standard deviation and can be used to assess the performance of operations through a series of calculations to determine a storage efficiency, distribution efficiency, a measure of spatial equity and adequacy of the operations. The temporal variation in the statistics will provide a measure of the reliability of operations and the consistency of the flow rate in open channels.

Managing irrigation schemes is site specific. However, Carter *et al.* (1999) propose a generic analytical framework to identify, quantify and evaluate the significance of water losses within irrigation schemes. The framework proposed consists of the following six steps.

1. Identify and quantify all flows, highlighting and categorising losses.
2. Quantify a realistic expectation for each loss.
3. Ask whether each loss matters or not, and identify priorities.
4. Identify the causes of priority losses.
5. Identify necessary and achievable actions to reduce/control priority losses.
6. Compose a remedial program of actions.

The difficulties associated with quantifying the losses in the previous steps are highlighted in the literature. However, this is the most important step; the indicator that is obtained from the measurements is really a secondary consideration.

Once quantified, performance indicators can be derived from the water balance. Even though a formal standardised set of indicators would be ideal, this would appear to be an unrealistic expectation. A generic water balance framework can be applied to the preferred indicators for a site specific situation. Given that the necessity for quantifying the water balance in an irrigation scheme has long been recognised, the reason for the current lack of data is probably a lack of resources for collecting these data. Available resources reflect the priorities of society which, as stated earlier, are changing through the CoAG reforms.

It is estimated that in 2000-01 the forty water providers surveyed by ANCID delivered 6,500 GL of water to irrigators who had an entitlement to about 8,000 GL. The replacement value of the distribution works used to deliver this water is estimated at $3.5 billion. A total of 3.1 million hectares of land is estimated to be within the designated irrigation areas managed by the forty water providers and in 2000-01 the delivered 6,500 GL was used to irrigate 1.2 million hectares. Therefore, on average, 5.4 ML was supplied to each irrigated hectare of land. This equates to an average depth of 540 mm of irrigation water applied. The gross revenue from the sales of water by the forty providers surveyed was $202 million, which equates to an average price of $31/ML.

This national averaging varies when the figures are considered on a state-by-state basis. On a per hectare basis, in 2000-01, Queensland and Victoria delivered around 4 ML/ha, compared to the 12 and 13 ML/ha delivered in SA and NSW, respectively. In 2000-01, WA had delivered, on average, 5.5ML/ha.

In 2000-01, only five of the forty surveyed water providers indicated their irrigation supply system consisted entirely of a piped system. However, over the four years that ANCID have undertaken the benchmarking surveys, conveyance efficiencies have increased, on average, from 72 to 82%.

Dalton *et al.* (2001) estimated that evaporation accounted for 2 to 3% of the water balance for distribution channels on cotton farms in Queensland and NSW. Seepage losses accounted for 2 to 6% and were estimated to be in the range of 1 to 23 mm/day for a heavy clay. These estimates and some other Australian channel seepage data (Table 3) are much lower than the seepage losses estimated by Burt (1995) for channels in the United States (Table 4). Banyard (1983) measured supply channel seepage rates varying from 3 mm/day to 60 mm/day in the Ord Irrigation Area, WA. In the same study seepage rates from drains varied from 8 to 1000 mm/day.

It is worth noting that the highest seepage rate measured by Dalton *et al.* (1999) was in a channel constructed in heavy clay, and the other Australian studies included in Table 3 reported lower seepage rates in lighter soils where a higher seepage rate would be expected. However, the interception of a prior stream with the distribution channel was thought to have contributed to a localised region of high seepage in the channel constructed in the heavy clay (Dalton *et al.* 1999).

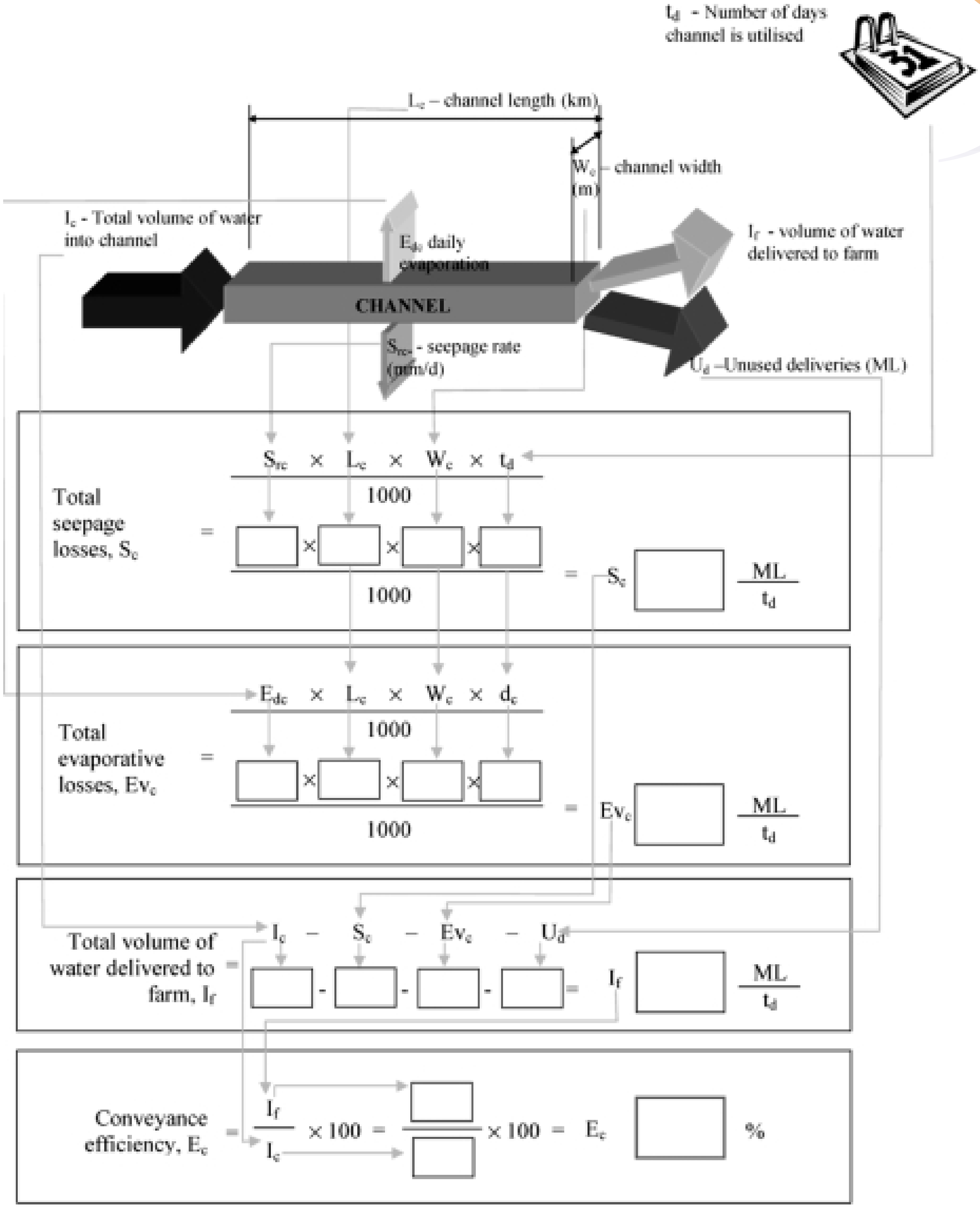
Table 3. Typical channel seepage rates measured in Australia (Raine 1999).

LOCATION	SOIL TYPE	RATE (mm/day)	SOURCE
Central Goulburn, Vic.	Alta clay loam	1.5 - 3.0	Holland (1997)
	East Shepparton fine sand	6.0 - 8.8	
	Erwin loam	3.1 - 4.7	
	Karook fine sandy loam	4.0 - 5.2	
	Wallenjoe clay	1.3 - 1.8	
Shepparton, Vic.	Broken sand	9.0 - 11.0	
	Gupna fine sandy loam	6.0 - 8.8	
Border Rivers, Qld	Heavy clay	1 - 23	Dalton *et al.* (1999)

Table 4. Approximate channel seepage losses in the United States (Burt 1995).

SOIL TYPE	RATE (mm/day)
Impervious clay loam	70 – 100
Clay loam, silty loam	150 – 230
Clay loam with gravel, sandy clay loam	230 – 300
Sandy loam	300 – 450
Sandy soil	450 – 550
Sandy soil with gravel	550 - 750

Figure 9. Template for calculating conveyance/distribution efficiency.



The water balance framework has to be built on data that are routinely collected during the operation of a conveyance and delivery system. This will necessarily involve a combination of methods for inferring the water balance from collected data, for example, using statistical methods and simulation modelling.

Performance indicators

The conveyance efficiency (E_c) recommended in the Barrett, Purcell & Associates framework is a ratio of the total volume delivered to the farm to the total inflow of the supply system (Figure 9, previous page). The distribution efficiency (E_d) is defined as the ratio of the water received at the field inlet to the volume of water supplied to farm boundaries. Multiplying E_c by E_d will give the combined efficiency of the conveyance and distribution systems.

Molden and Gates (1990) defined a suite of performance measures for evaluating irrigation water delivery systems that encompasses both the spatial and temporal variation of the system. This suite of performance indicators comprises measures of adequacy, efficiency, dependability, and equity of water delivery, as follows:

- adequacy of delivery is a measure of the reliability of the water supply, schedules and the capacity and management of the hydraulic structures to deliver the water at the required time
- efficiency includes not only the traditional conveyance measure, i.e. the indication of the relative amount of water lost from a channel, but also encompasses the over supply case
- dependability is a measure of the temporal uniformity of the ratio of the delivered amount of water to the required or scheduled amount
- equity is the delivery of a fair share of water to users throughout a system, which is often a subjective measure, therefore Molden and Gates defined equity as being spatial uniformity of the ratio of the delivered amount to the required or scheduled amount.

Small and Svendsen (1990) categorise performance measures of irrigation systems as process measures (relating to a system's internal operations), output measures (relating to a system's final output), and impact measures (pertaining to the effects that the system's outputs induce in its larger environment).

Desilting a channel.

Techniques for reducing losses

Physical solutions

There are a number of methods available to remediate seepage losses, some of which are mentioned in the various case studies that follow in the next section. A full explanation of these techniques can be found in *Open channel seepage and control. Vol 2.1 Literature review of earthen channel seepage remediation techniques* (2001), published by the Australian National Committee on Irrigation and Drainage. They include the use of the following:

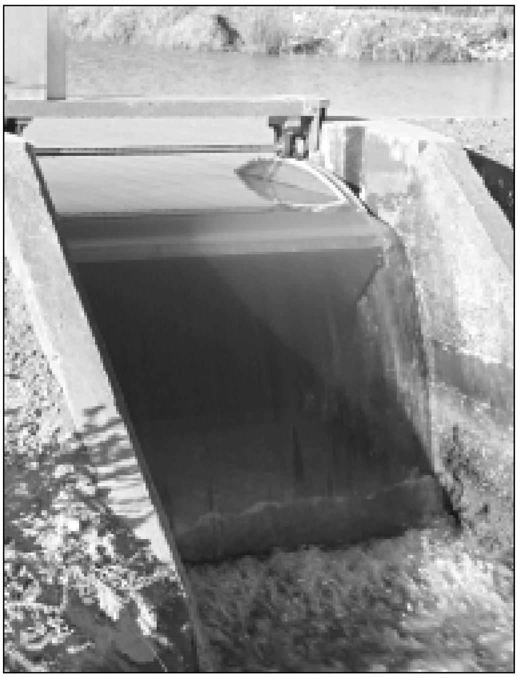
- earth liners, such as bentonites and other soil sealants
- hard surface liners such as concrete, grouted fabric mats, flumes, pipes, tiles and bricks
- flexible membrane liners constructed from geosynthetic clay, asphalt or plastic materials.

Groundwater intervention is another technique to mitigate the seepage problem by recovering rather than eliminating losses. It includes the use of the following:

- core trenches that are vertical subsurface barriers designed to limit flow into surrounding soil
- groundwater pumping, which is extremely expensive in most cases
- vegetation grown next to channels specifically to manage the adverse impacts of seepage
- tile drains.

Technological solutions

A pilot scheme using technology developed by Rubicon Systems Australia has been established to optimise the distribution efficiency on an irrigation channel near Tatura, Victoria. The technology involves using radio telemetry and software to remotely control channel gates on the Central Goulburn No 2 Channel (see location in Figure 5). The two-year pilot scheme is managed by Goulburn-Murray Water (G-MW), and involves water supply to 51 customers through forty regulating structures and 150 supply outlets.



Remote-controlled channel gates allow managers to control and operate the whole channel network remotely and in response to changes in the system.

The aim of the $1.6 million project is to use state-of-the-art technology to improve irrigators' water use efficiency and, as a result, increase environmental flows to the Murray and Snowy rivers. This technology links electronically controlled channel gates through radio telemetry with computer software to enable the whole channel network to be operated remotely and in a dynamic manner. These technologies have resulted from extensive research with Melbourne University into the application of control technologies in other industries, and it is claimed they can deliver a service similar to that of a fully enclosed pipe network.

Included in Rubicon's suite of technologies is a new approach to customer ordering that uses WaterLINE (Interactive Voice Response (IVR) based technology) or an Internet 'Web based' interface. On attempted lodgement of their chosen order, time, date, duration and flow rate, the system will check for available capacity. If it is verified, the order is accepted and confirmed. If the available capacity is not verified, the customer will be offered the opportunity of trying another date and time or they may lodge the order and allow a planner to schedule the start as they would under the present system. Obviously, on channel systems with some capacity constraints, the first in-first served principle or other sharing rules would apply.

Another component of the system is a new "FlumeGate" designed to replace the current Dethridge wheel by simply bolting into the concrete emplacement and removing the old wheel. This gate will connect into, and be part of, the total network and can be manually operated on-site or remotely controlled by a host system.

Benefits offered by this gate are reduced head loss for greater land command, constant actual delivery information, alarm options to identify open and close gate configurations, and an interface to automated on-farm systems.

The channel network selected for this pilot is located within the Central Goulburn Area of G-MW's gravity irrigation delivery network. The channel network, known as the CG 2 comprises 74 km of channel supplying water to fifty one individual customers with flows up to 140 ML/day to supply water to a variety of cultures including flowers, fruit, tomatoes, fodder crops and varieties of annual and perennial pastures. Average annual flows into the system in the last five years are 13,100 ML, with average deliveries to farm of 10,800 ML.

Installation of gates started in May 2002 with the intention of the new system being fully functional for the start of the irrigation season in August 2002.

The pilot project is expected to be complete in May 2004. If successful, the technology will be promoted throughout Victoria's irrigation networks and is likely to have broad application in Australia and overseas.

Regional case studies

The following case studies are taken from ANCID (2001) and highlight some rehabilitation work that has been undertaken in recent years to improve the performance of various conveyance systems.

Emerald Irrigation Scheme, Queensland

The Emerald Irrigation Scheme was established in 1968 and draws water from the Nogoa River in the Central Highlands of Queensland to irrigate an area of 12,000 ha (see location in Figure 5, page 14). Most of the channels in this scheme were originally built in shallow soils and in some cases the channel beds are excavated up to 1.0 m into the underlying decomposed basalt. A rise in watertable levels in part of the area was attributed to seepage from the channels.

Between 1978 and 1984 several unsuccessful attempts were made to seal sections of the channels with local clays and bentonite. Why they were unsuccessful is not known. Following these unsuccessful attempts three different flexible membrane liners were tested in sections of the channels. The three liners chosen were an elasticised polyolefin, a nylon reinforced chlorinated polyethylene and a Fabrene TMBB.

Results from these trials showed that all fully exposed liners failed on batters within 4 years. The polyethylene sheeting tended to split away from the nylon fabric in the nylon reinforced chlorinated polyethylene; there were problems with the Fabrene TMBB creeping down the batter after 5 to 7 years and there were cases of tension failure along the exposed batter. Many of the joins in this fabric also failed. All liners were punctured by sticks, stones and other sharp objects.

The trial did show, however, that all the liners placed on the bed of channels or fully buried on the side slopes performed well. In some cases the localised high watertables were eliminated and in other cases the watertable was reduced by up to a metre. The trial reclaimed about a hundred hectares of land with unit costs ranging between $1600 and $4800/ha.

Mareeba, Dimbulah Irrigation Area, Queensland

This scheme was built over 40 years ago and was developed specifically for growing irrigated tobacco (see location in Figure 5). The assumption was that 40% of the increased value of production would be returned to the State and Commonwealth governments through increased taxes and charges, and if this was greater than interest redemption on the capital cost, the scheme was considered viable. The scheme included the first major dam built in Queensland, mainly as an irrigation supply. These days there is very little tobacco grown in the area and the irrigation channels now supply water mostly to sugarcane and other crops including pasture, mangoes, citrus, coffee and vegetables.

The channel investigated for this case study was built with 50 mm unreinforced concrete. The rational for not reinforcing the channel at the time of construction was probably that the concrete was used simply as a waterproof membrane and not a structural membrane. For this design case 50 mm of concrete was enough to stop seepage and for erosion protection. Reinforcing would have required twice the thickness of concrete to stop the steel rusting. Subsurface drainage was installed before laying the canals, however, constant seepage caused piping problems within the earthworks resulting in joint displacement and cracking in the concrete. These cracks and joints were traditionally repaired using cement and epoxy based products, but this has always been a temporary solution and a more permanent solution was sought.

The concrete was cleaned with high pressure sprays and a sand-cement mix used to fill the voids and sharp edges to avoid puncturing the liner. A 2 mm thick exposed HDPE liner was applied and anchored in trenches dug at the top of the channel. The amount of lining required for the trial was 55,000 m^2 at a cost of $9.00/$m^2$.

The trial has been successful with no major problems identified after two years and discharge to subsurface drainage virtually eliminated. However, there may be some degradation over a longer time period (see previous case study).

The study did highlight issues with grass fires and a possible safety hazard to people and animals associated with the slipperiness of the material. These problems suggest that best management practices for using this material should include keeping the area free of dead grass, sterilising the anchor trench backfill to minimise the risk of fires, and installing rubber escape mats at 100 m intervals to stop people and animals being injured.

Caldwell and Jimaringle Channels, Murray Irrigation Ltd

A 0.31 mm thick plastic liner was placed sixty centimetres below the channel bed. An analysis of using the plastic liner, replacement of channel with pipes or clay lining the channels indicated that the plastic liner was the most economic option.

The liner was placed at this depth to ensure a substantial weight on the liner in case there were negative pressures generated from groundwater when the channel was drained. Localised groundwater levels have fallen as a result of these liners being installed, suggesting they are providing some seepage control.

Implementation and adoption

The following is taken from Marshall and Bowman (2000) as an example of the adoption of technology to increase the efficiency of not just the conveyance system but also the irrigation systems which it supplies.

Rehabilitation of the Loxton Irrigation District

(Adapted from Marshall and Bowman, 2000)

Background

The Loxton Irrigation District in South Australia (see location in Figure 5, page 14) services two hundred and twenty farms that irrigate about 3,200 ha. Crops produced in this area include citrus (mainly oranges), wine grapes and other crops such as almonds and vegetables.

A low-pressure pumping station located on the river bank draws water from the River Murray. The water is then delivered through a network of about 65 km of open channels and low-pressure pipelines. Water is delivered at low pressure or under gravity to the farm gate through a system with a limited supply capacity. Generally it is re-pumped by the individual growers through to their on-farm irrigation systems.

Delivering water in a timely manner and so that it matches each grower's demand is hampered by the limited supply capacity of the delivery system, which results in irrigation practices on-farm that are below their optimum efficiency. The lack of confidence in the availability of water leads to over-ordering and over-application. This over-ordering compounds the limited supply capacity problem. The suboptimal irrigation practices in turn create high drainage volumes contributing to rising groundwater levels and saline flow to the River Murray.

Rehabilitation

The existing pumping station, open channels and low-pressure pipelines are being replaced with a high-pressure system designed to deliver water to the property boundary at a minimum pressure of 35 m. This high-pressure delivery system will remove the need for the water to be re-pumped at the delivery point. The capacity of the distribution system is being increased with the hope that the increased security of supply and improved timeliness of supply at higher pressures will result in more efficient application of water.

Technology

The improved delivery flexibility provided by the new distribution system is matched by an improved telephone and internet ordering system. The internet ordering system allows growers to see the availability of water in the system and place their order accordingly.

The rehabilitation of the Loxton Irrigation District is due to be completed in March 2005 and it is estimated 4.8 GL of water savings will be generated (Hansard 2000).

Emerging issues

At the time of writing, media coverage has been focused on calls for the piping of Australia's open channels. This media attention demonstrates the level of concern that society is expressing about the use of water for irrigation.

Prioritising refurbishment works is the first step in addressing these concerns, followed by a rigorous economic analysis of the benefits and the costs of piping water in the priority areas. It is also important that any plan to refurbish an existing system considers all the implications in the context of the whole system. This whole-of-system concept is explored in Chapter 6.

CHAPTER 5

APPLICATION TO FIELD

Current understanding

Applying the dual compartment toolbox approach that is central to the Barrett, Purcell & Associates framework provides a clear distinction between irrigation and agronomic (crop) water use efficiencies and indices. This distinction is important in terms of reporting a measure of performance.

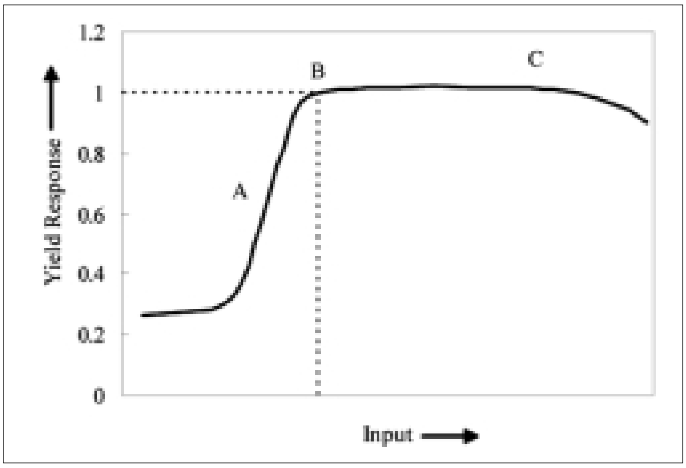
Generally, improving water use efficiency or a crop water use index will require the amount of water a crop transpires to be maximised and the losses that occur as the water moves to the plant to be minimised.

A crop water use efficiency or index compares the yield or economic return from the crop to the amount of water the crop transpires. An irrigation efficiency or index compares the amount of water the crop transpires, the water stored in the rootzone, the economic return from the crop or yield to the amount of water that is applied. See Figure 3, page 10, for some examples.

In some cases it may be desirable to limit the amount of water a crop transpires, e.g. to improve the fruit quality (deficit irrigation), and in this case maximising transpiration is not the objective of irrigation. A water use economic index would be needed to measure the improved performance when transpiration is intentionally restricted.

When irrigation application is below optimum there is generally a positive response in yield for each unit of irrigation water applied (the steep response curve A in Figure 10). Beyond this optimum point (B in Figure 10) there is, on well drained soils, no further increase in yield for each extra input of irrigation water. However, because irrigation is a very small percentage of the input costs and the uncertainty of the location of point B, applying more water than is necessary (operating on the flat part of the curve between points B and C in Figure 10) provides cheap insurance for a high value crop. Applying water at rates beyond point C will result in a yield response penalty, which would be an incentive to apply less water. However, between points B and C there may be little financial incentive to reduce water application (see Stirzaker, 1999).

Figure 10. Input response curve for water (Stirzaker 1999).



Howell (2001) presents four options for improving irrigation efficiency at a field level, based on Wallace and Batchelor (1997):

Agronomic. Crop management to enhance capture of rainfall or reduce water evaporation (e.g. crop residues, conservation till, and plant spacings); improved varieties; advanced cropping strategies that maximise cropped area during periods of lower water demands or periods when rainfall may have greater likelihood of occurrence or both.

Engineering. Irrigation systems that reduce application losses, improve distribution uniformity, or both; cropping systems that can enhance rainfall capture (e.g. crop residues, deep chiselling or para-tilling, furrow dyking and dammer-dyker pitting).

Management. Demand-based irrigation scheduling; slight to moderate deficit irrigation to promote deeper soil water extraction; avoiding rootzone salinity yield thresholds; and preventive equipment maintenance to reduce unexpected equipment failures.

Institutional. User participation in an irrigation district (or scheme) operation and maintenance; water pricing and legal incentives to reduce water use and penalties for inefficient use; and training and educational opportunities for learning newer, advanced techniques.

Management is an important aspect and as well as being listed explicitly is also inherent in the other three options. Therefore, savings in water can be expected through improved management, which results from enhanced understanding of the system.

Making improvements in one part of the system will have implications for other parts of the system (e.g. demand based irrigation scheduling requires flexible delivery of water or an on-farm storage facility). Therefore, increases in water use efficiency will require simultaneous improvements in each of the options.

The many variables that contribute to the application efficiency of water in a particular field include the location of the enterprise, the evaporative losses associated with the location and time of year, the deep drainage and surface runoff volumes and the lead time required for ordering water. Lower efficiencies could be expected where the lead time is greater and there is no on-farm storage available because of the reduced flexibility to apply water to meet crop needs on demand.

Although some deep drainage losses contribute to lower application efficiency, they can lead to a higher crop water use index in the long-term if they leach salts out of the rootzone and maintain a healthy soil. Surface runoff will contribute to a lower application efficiency of a single event, however, if it is recycled and used for another irrigation the field and farm efficiency are increased.

Leaking fields

Before the efficiency of an irrigation event can be measured the purpose of applying water has to be defined. The purpose for which irrigation is applied includes, but is not limited to, one or more of the following: to refill the rootzone, flush salts, cool the crop or warm the crop to stop frost damage. Defining the purpose of the irrigation will provide guidance on measuring how efficiently water was applied.

Measurement

Methods to evaluate application efficiencies and distribution uniformities of different irrigation systems are included in Raine (1999) and the International Standards listed in the Appendix. The International Standards include templates for the measurements needed to evaluate each irrigation system and the equations to calculate the required efficiencies and uniformities.

Estimating application efficiency

ANCID (2002) reported on the percentage of irrigation methods for 808,000 ha serviced by forty irrigation water providers in Australia. Over 80% of this land is irrigated using the border check method, mostly on pasture, fodder and cereal crops. Furrow irrigation was reported as the next common irrigation method (13%) followed by sprinkler (4%), drip (2%) and micro-sprinkler (1%).

Worldwide, average application efficiencies of different systems are reported as being the following:

- surface: 60 to 90%
- sprinkler: 65 to 90%
- drip: 75 to 90%.

However, these efficiencies can be misleading and depend on soil type, moisture conditions before irrigation, depth to groundwater, the crop being grown, management practices, and quality of irrigation water.

Conceptually, one would imagine that a drip system would be a more efficient way of applying water, but this premise has been shown, in some cases, to be false (Hodgson *et al.* 1990, Willardson and Wagenet 1983). It is the management of the system for a particular soil and crop combination that is the important input to improve irrigation efficiency. A technology that can lead to potentially high efficiencies, such as drip irrigation, still has to be managed to take full advantage of that potential.

The biggest challenge faced when trying to determine the efficiency of a single irrigation or an irrigation season, at either field or farm scales, is accurately measuring all the components of the water balance required to calculate this efficiency. Drainage past the rootzone is a particularly difficult component to measure and can be estimated by difference, i.e. other components are measured or estimated and the drainage is calculated as follows:

> *drainage = inputs (irrigation water applied + effective rainfall) minus outputs (crop water use + surface runoff + change in soil moisture).*

Application efficiency

While relatively simple in concept, there is potential for confusion in interpreting application efficiency. The source of this confusion is varying interpretation of the spatial bounds (paddock, farm, irrigation project or catchment), and time (single irrigation, growing season or year). As well, accounting for the contribution of rainfall to crop water use is often problematic. An example definition is included in Figure 3, page 10.

Water storage capacity of the soil is an important consideration that is often overlooked. For example, if the rootzone of the soil to be irrigated can store only 100 mm, but 400 mm is applied with absolute uniformity, the water application efficiency will only be 25%. In contrast to this, under-irrigation can achieve a 100% water application efficiency every time, but the crop yield is likely to be reduced.

Adding a leaching fraction is important for an irrigated system in a low rainfall area to stop salts building up in the rootzone. A balance must be struck between reducing water applications in an attempt to improve application efficiency and managing the concentration of salts in the soil.

Distribution uniformity

Distribution uniformity (DU) is a measure of how evenly water is applied during an irrigation event. This uniformity of application can have a big effect on crop yield and optimum water application.

There are several interpretations of DU in the literature, but a common measure for surface irrigation systems is to divide the average depth infiltrated calculated from the quarter of the field with the lowest infiltrated depths, by the average infiltrated depths. This is called the 'low-quarter DU'. An alternative measure, often applied to sprinkler irrigation, is the Christiansen Uniformity Coefficient (CU), which is essentially a ratio of the sum of the variation of depths from the average depth to the sum of all the depths.

Uniformity of sprinkler irrigation is often evaluated by measuring the application depths using catch cans. Emitter discharges are measured in drip systems to evaluate the uniformity of application by considering the intake opportunity time.

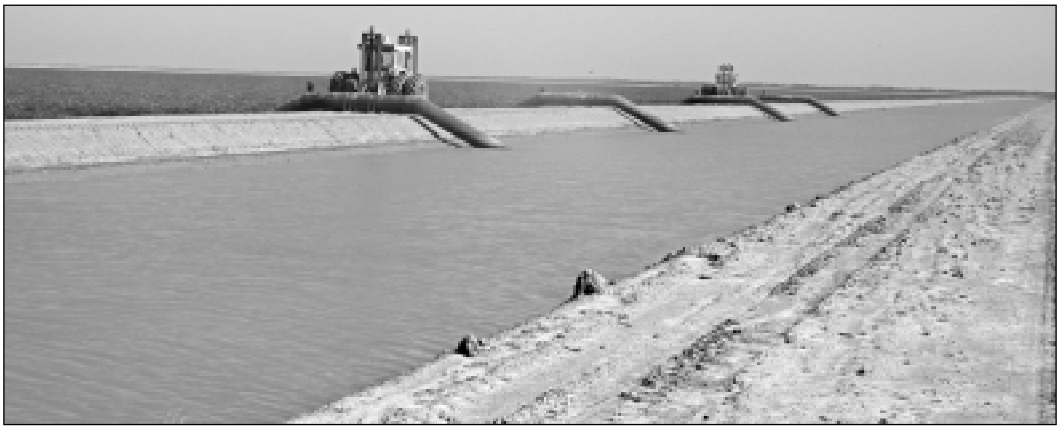
Uniformity of application in surface irrigation systems is measured directly by soil moisture changes or estimated by the use of models such as SIRMOD that require inputs on the infiltration characteristics of the water into the soil and movement of the water advancing and receding down a furrow or bay.

Distribution uniformity is expressed as a percentage (between 0 and 100%). Common values for existing sprinkler systems range between 60 and 80% and for furrow irrigated fields, 50 and 60% or less. The uniform application of water in a field is important, but it has to be considered together with the efficiency of the application.

Interaction between application efficiency and distribution uniformity

Understanding the relationship between application efficiency and distribution uniformity is crucial for improving in-field irrigation performance. A uniform application is required for an efficient application. However, uniform application does not imply an efficient application. Some irrigators may knowingly over-apply to ensure that one area of the field receives the minimum required water and thereby over-water other areas of the field. This situation comes about because of the spatial variability of the irrigation system, which in turn influences the ability to increase the uniformity of application.

The combination of the distribution uniformity and application efficiency does not fully account for crop yield-reducing deficits. Consider the situation with a surface irrigation system where application is reasonably even and runoff and deep percolation losses are small. Applying the uniformity coefficient and application efficiency calculations would indicate a uniform and efficient system. However if a large deficit existed, and only a small proportion of the irrigation deficit was met, then the overall irrigation may be grossly inadequate.



Irrigation with over the bank siphons

Performance Indicators

Evaluating application efficiency has the same spatial and temporal boundary constraints as all other parts of the irrigation system. The methods for evaluation range from measuring the inflow and outflow from a single event, to estimating the inputs and outputs over an irrigation season or a number of seasons. Simulation models can be used to investigate the potential efficiency of a system with respect to the many variables associated with the system and the random nature of those variables.

There are many water use indices that can be applied to evaluate the system, but the most important step within the Barrett, Purcell & Associates framework is to clearly define the units used in the index. These crop water use indices are a measure of the agronomic performance of the crop (yield and economic return) in relation to the irrigation water applied.

In terms of a true efficiency measure, the water balance is the key consideration. This water balance requires measurements or estimates of some or all of the following:

- the deficit before irrigation
- actual crop evapotranspiration
- effective rainfall
- amount of irrigation water applied
- runoff
- drainage below the rootzone
- the leachate requirement based on the salts in the irrigation water compared with the salts stored in the rootzone.

All these components can then be used to estimate the application efficiency, the uniformity of the application, the adequacy of the application and the effectiveness of the irrigation in meeting the target application. Reporting the efficiency derived from these values is meaningless without including the water balance used to calculate the preferred measure.

Commercial products

Managing irrigation at the field scale can be improved by quantifying the water balance. Understanding where savings can be made in this water balance is a necessary step to achieving improvements in application or irrigation efficiency.

Soil moisture must be measured or estimated to calculate the water balance, and there are a range of products on the market to do this, from the very simple, such as the FullStop® wetting front detector to the complex, such as neutron probe moisture meters. For a list of commercial soil water monitoring products see booklet number one in this *Irrigation Insights* series, *Soil water monitoring* (2000), published by Land & Water Australia.

Recently there have been several performance evaluation products developed specifically to measure all aspects of the in-field water balance required to calculate field application efficiency. These products include loggers to record the rate and depth of flow down a furrow, catch cans to measure application depths, meters to measure in-flows to fields, flumes to measure run-off, weather stations, groundwater bore monitoring and yield monitoring devices.

Whether the product used to quantify the water balance at the field scale is simple or complicated, what is most important is measuring, monitoring and managing the system to achieve and maintain high application efficiencies and uniformities.

New techniques

New techniques for improving the effectiveness of all types of irrigation systems can be found in many agriculture water-related journals. The common thread in most new techniques is the management component and, in a lot of cases, the requirement to measure the irrigation event. Some of the new techniques developed in recent years include:

- Centre pivots and linear move systems, which have been improved by moving the water outlet closer to the ground by using drop tubes. LEPA (Low-Energy Precision Application) multi-functional centre pivot systems were developed in Texas in the early 1980s. Bubblers and socks or sleeves have become the two most commonly used LEPA application devices.
- Partial rootzone drying, which was developed in grapevines and pome and stone fruit by South Australian and Victorian researchers. Part of the root system is slowly dried and the remaining roots are kept well watered. It is thought that the half of the rootzone that is drying sends a signal to the rest of the plant that it is in stress, which responds by narrowing the stomata opening to avoid excess moisture loss. However, the plant also responds to the adequate water supply to the other half of the roots and the leaves remain hydrated. The cycle is reversed every couple of weeks or as dictated by the local climate, to maintain a portion of the rootzone in the "drying" state.
- Development of integrated real-time irrigation scheduling systems.
- Irrigation scheduling methods using remotely sensed crop temperatures.
- Deficit irrigation, which is the practice of finishing irrigation prematurely before the end of the crop cycle, or applying less water than required to replenish the soil moisture deficit at each irrigation. This has been practised in cotton, winegrapes and corn.
- Alternate furrow irrigation is another practice used to conserve water, and has been trialled in cotton and soybean. This technique (also known as skip row or wide-spaced irrigation) was found to improve water use efficiency in sugarcane grown on light textured alluvial soils in the Burdekin, however, yields were reduced. No improvement was observed for alternate furrow irrigation over every furrow irrigation on cracking clay soils.

Linear move irrigation systems have become more popular in Australia as an efficient way of applying water to a variety of crops and pastures.

Implementation and adoption

Delivering improved water use efficiency across the Murray-Darling Basin

Mark Skewes, Rural Solutions, South Australia

The objective of this project is to provide irrigators and water management agencies with a set of tools to assess and monitor water use efficiency. The project is developing a user-friendly, practical and affordable method for assessing, recording, and reporting water use efficiency for irrigated horticulture within the Murray-Darling Basin.

Initial development work is occurring in the Cobdogla Irrigation Area in the South Australian Riverland, with a primary focus on districts with pressurised water delivery systems.

The method requires key data to be collected at the farm level, in enough detail to benefit irrigators. The project provides a process for compiling and summarising farm level data so that it facilitates consistent and meaningful reporting at property, irrigation district and regional scales.

Two modules are being developed, the Irrigation Inventory Module (IIM), and the Farm Level Water Management Module (FLWMM). The modules operate at different scales within the landscape and will have different end users.

The IIM uses geographic information system (GIS) technology to compile and summarise property information and produce property plans. The property information is combined with climatic data and crop water requirement calculations to produce general indicators of water use efficiency at the district and regional scale.

The FLWMM is a toolkit for assessing water use efficiency at the farm level. Information on planting patches and irrigation valve units is combined with irrigation records and climatic data to provide indicators of water use efficiency at the crop type and valve unit level. The FLWMM generates outputs and indicators to help irrigators improve irrigation management, as well as provide information required by processors, marketing organisations and water management agencies. The FLWMM also exports selected data and indicators to the IIM for compilation and summary at district and regional scales.

Both modules use water balance calculations to derive water use efficiency indicators. The IIM compiles annual water meter readings and calculated crop water requirements at whole farm scale to provide an Annual Water Balance Index at the district level.

The FLWMM uses a daily water balance calculation, using grower records of irrigation events and water meter readings to produce a range of indicators including:

- Field Application Efficiency (irrigation water available to the crop as a proportion of water received at the field inlet)
- Irrigation Water Use Index (total product per megalitre of irrigation water applied)
- Net Irrigation Index (water received at field inlets plus effective rainfall as a proportion of calculated crop water use for maximum growth under non-limiting conditions).

Both modules are being developed. Testing of initial draft versions is promising.

Already growers who are involved in the trial sites at Cobdogla are reporting benefit from their involvement in the project, simply as a result of recording information in a structured way, allowing review of the season's irrigation management.

Peel and Upper Namoi valleys

The following case study comes from Project Haymaker; *How much water does my soil need?*, a NSW Agriculture, Queensland Department of Primary Industry and Rural Industries Research and Development Corporation project (see location in Figure 5, page 14).

NSW Agriculture field and research officers started a project called *Haymaker* for irrigation farmers in the Peel and Upper Namoi Valley areas in 1993. The objective of this project was to provide guidelines for efficient water use by irrigators. A soil assessment project provided the basis for the recommendations made by the project team.

The information provided included water holding capacity and the physical characteristics of the soils that influence infiltration rate at the surface and down the profile. These characteristics included clay dispersion, salinity, sodicity, surface crusting, and compaction. Before this information was available, broad guidelines and rough estimates were used for the design and management of irrigation systems in the area.

The motivation for the project came from the observation that many lucerne crop yields were below maximum and some were only achieving 30% of potential yield. Moisture stress was identified as a factor in these reduced yields. NSW Agriculture officers recognised that objective information on the physical characteristics of soils was the first step in achieving higher irrigation efficiencies and so a major soil sampling and analysis program was conducted.

Twenty-seven representative soil types from the area were identified in the 13 sites that were sampled. The soil types identified ranged from light textured sandy loams to heavy textured grey clays. Over 77% of the soils sampled were rated as being favourable for irrigation with twenty one of the twenty seven samples rated as good, very good or excellent and six soils rated as poor, difficult or unfavourable for irrigation.

From the sampling regimen an irrigation matrix was developed listing the Plant Available Water (PAW), Readily Available Water (RAW), irrigation rating and special consideration for each of the identified soil types in the area. Irrigators are encouraged to match their soil type with one from the matrix and, using a basic guide to infiltration rates and permeability, determine the appropriate water application rate for each paddock. The irrigator then uses a trial and error process to visually assess the runoff and depth of water penetration (using soil probes) over a range of water application rates.

If used correctly, the basic information on soil water holding capacity and infiltration rate provided by this project will improve the efficiency of irrigation. These improvements will come as a result of estimating the amount of water required at each irrigation, the right time to start irrigating (using evapotranspiration data) and a rate of application suitable for the soil being irrigated.

Murrumbidgee catchment

The following case study comes from some benchmarking work on the irrigation of maize in the Murrumbidgee (see location in Figure 5, page 14). The study was undertaken by Michael Reynolds, Water Use Efficiency Officer, NSW Agriculture, Wagga Wagga. The aims of monitoring irrigation events for this benchmarking work were to determine the right amount of water to apply to a crop and the right time to apply it. This timely application can lead to increased yields and profits.

Background

The aim of the study was to help farmers make irrigation management decisions in conjunction with agronomic advice on the timing of irrigation events that would lead to an improvement in crop yield and increased profits.

Benchmarking the total amount of water used per growing season and relating this to yield and profit provides local data for irrigators. These data can then be used to make decisions on improvements to irrigation systems and irrigation timing.

The trials

Data were collected during the 2001-2002 growing season from a mixed farm in the Sandigo District, about 25 km east of Narrandera. The farm uses surface irrigation on a row crop layout. The crop (maize) was irrigated ten times during the season at an average of 40 ML per irrigation over 49 ha of crop.

Data collected included:

- total amount of water delivered to the field
- total amount of rainfall per growing season
- total amount of runoff
- average evapotranspiration figures per growing season
- crop water use data
- economic data.

Data were collected by both the owner and NSW Agriculture's Water Management staff using a variety of techniques. Water delivered to the field and runoff were calculated using water flow meters while crop water use data were collected using both EnviroSCAN® soil moisture probes and tensiometers.

Results

The following results are used in the field performance measures shown in Table 5.

A	crop yield	538 t
B	area of crop	49 ha
C	irrigation water applied to crop	396 ML
D	rainfall during growing season	150 ML
E	total income	$12,484
F	total variable cost	$5,200

Table 5. Field performance measures.

FIELD PERFORMANCE MEASUREMENTS	CONVERSION FORMULAE	FROM RESULTS ABOVE	RESULTS
Gross production over area planted	Crop Yield (t)÷Area of Crop (ha)	A÷B	11 t/ha
Irrigation WUI	Crop Yield (t)÷Irrigation applied (ML)	A÷C	1.36 t/ML
Water use per hectare	Irrigation applied (ML)÷Area of Crop (ha)	C÷B	8.1 ML/ha
Gross production per total water applied	Crop Yield (t)÷(Irrigation applied (ML) + Rainfall)	A÷(C+ D)	0.99 t/ML
Gross margin per hectare	(Total Income ($)-Total Variable cost)÷Area of Crop (ha)	(E-F)÷B	$1489.60/ha
Gross margin per megalitre	(Total Income ($) -Total Variable cost)÷Irrigation applied (ML)	(E-F)÷C	$184/ML

The study is developing benchmarking data over a number of years to assess improvements to irrigation management techniques. This is a preliminary report from the first irrigation season of a three-year study.

From the data collected, it is evident that scheduling irrigation according to soil moisture monitoring data increases water use efficiency while maintaining above average yields. The gross margin/ML of $184/ML for the study farm compares well with the average for the Murrumbidgee Valley of $140/ML.

Lockyer Valley, Queensland: the benefit of improving the uniformity of irrigation applications

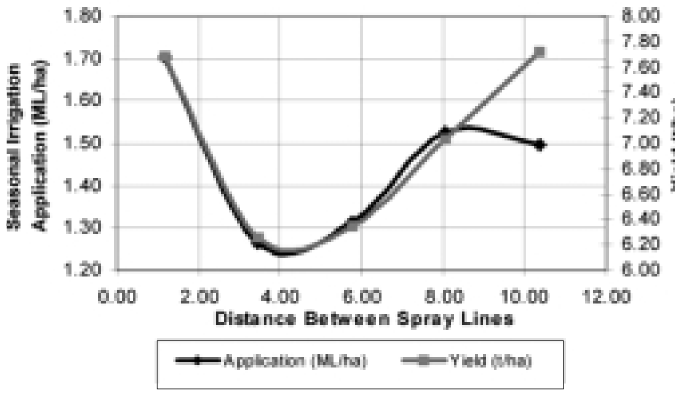
Evan Howard and Steven Raine, National Centre for Engineering in Agriculture, Toowoomba, Queensland.

Irrigation is an essential component of horticultural production systems as it has a significant impact on the quantity and quality of produce and hence, economic viability. Queensland Fruit & Vegetable Growers Ltd (QFVGs) has been providing irrigation performance evaluation and advisory services to horticultural producers as part of its *Water for Profit* program since 1999. Monitoring of infield application systems in many regions has identified significant opportunities for increasing profitability through improvements in the evenness of infield irrigation applications. In nearly all cases, the patterns in the volumes of water applied across the field have been found to be closely correlated to a range of crop growth, quality and yield data. In the Lockyer Valley, the distribution uniformity of irrigation systems typically ranged from 65 to 75%, compared with a target uniformity of greater than 85% for high value horticulture. Recent improvements in application system performance for this region have been estimated to have generated an extra $20 million a year through increased water use efficiency, yields and produce quality. The farming enterprise operated by Chris Jackwitz provides an example of the range of benefits associated with improving in-field irrigation uniformity.

Chris grows cauliflowers in the Tenthill area of the Lockyer Valley and uses a solid set irrigation system to irrigate his crops. The system consists of 50 mm aluminium pipe with the sprinklers positioned every 9.1 m along the pipe. At the time of testing, every sprinkler was fitted with 2.38 mm diameter nozzles operating at about 270 kPa. The laterals were positioned 14.4 m apart. With the help of QFVG's *Water for Profit* program, Chris measured his irrigation performance and developed a strategy to increase the efficiency of his irrigation and increase his profitability.

Monitoring showed that about 80% of the rubber seals joining the pipes were worn or non-existent. As a result, about 12% of the irrigation water applied was lost through coupling leakage and never made it to the crop. The sprinklers were old and many needed replacing. Some had seized and did not turn and some needed new nozzles. These issues combined to make Chris's

Figure 11. Variation in irrigation application and cauliflower yield between solid set irrigation laterals.



irrigation very uneven. Some of his field was receiving more water than other areas and other areas were not receiving enough water and were stressing (Figure 11).

The evenness of irrigation is measured by a Distribution Uniformity (DU) test. For high value horticultural crops, *Water for Profit* recommends a DU of 85% or above. Chris's system had a DU of 67% which was slightly below the Lockyer Valley average. The unevenness of the irrigation meant that his cauliflowers matured at different rates and multiple pickings were required to harvest the crop.

By replacing the worn rubbers, sprinklers and nozzles, Chris eliminated the water loss through the couplings and improved the evenness of water application to a DU of 77%. While the DU of the application system is still below the recommended levels (>85%), Chris believes that the improvement in uniformity achieved has already resulted in an increase in production of from 15 to 20%. Increasing the evenness of application also improved crop consistency and reduced the number of harvesting passes from five to three per crop. This reduced the cost of harvesting the cauliflowers from $2.00/carton to $1.50/carton. At 1500 cartons/ha (600 cartons/ac), the improvement in crop evenness saved Chris an extra $750/ha in harvest costs. The increases in crop yield and consistency and reduction in harvesting costs in this case paid for the maintenance costs associated with replacing the worn rubbers and sprinklers within the first year.

Emerging issues

At the dawning of the new century, water reform has become the major issue for the irrigated agricultural industry in Australia. Water reform is driven by the CoAG agreement to implement policies to obtain full cost recovery of water delivery, establish clearly specified water entitlements and arrangements to enable trade in those entitlements and recognise the environment as a legitimate user of water. The political water reform process has generated public debate over the last 10 years that in turn has highlighted the need for all involved in the irrigation industry to demonstrate a duty of care with respect to the distribution and use of water.

The calculation of some of the efficiencies mentioned depends on the ability to determine the evapotranspiration of the crop; this is not a trivial matter and once a simple reliable method is found and standardised, reporting of WUE will become more commonplace. The standardisation of a method to predict crop evapotranspiration was the subject of a recent workshop convened by the National Program for Sustainable Irrigation. The aim was to obtain agreement from all state and federal agricultural and natural resource agencies to adopt the Penman-Montieth method as outlined in FAO 56 (Allen *et al.* 1998).

Direct measurement of crop evapotranspiration is very difficult; however indirect measurement, such as soil moisture content, does provide a good indicator of the amount of water taken up by the crop if the inputs (irrigation and effective rainfall) are known and the instrument used has been calibrated to site specific conditions. This does require, however, an assumption of the amount of water moving below the rootzone. Additional measuring devices to measure soil water deeper in the profile can provide an estimate of the movement of water below the rootzone.

CHAPTER 6

WHOLE-OF-SYSTEM EFFICIENCY

Current understanding

Water use efficiency is broader in scope than most agronomic applications, and must be considered on an irrigation district or catchment scale. Howell (2001) suggests improving WUE involves:

- increasing output per unit of water (engineering and agronomic management aspects)
- reducing losses to unuseable sinks, reduce water degradation (environmental aspects)
- reallocating water to higher priority uses (societal aspects).

Quantifying and qualifying the water balance at the whole-of-system scale is the first requirement to achieving the improvements in the three areas listed. The 'losses' at the whole-of-system level must be measured to calculate this water balance. Carter *et al.* (1999) identified ten categories of losses and grouped them into three different classes as follows:

Atmospheric losses

1. evaporation from open water (in reservoirs, canals, and fields)
2. wind drift and spray evaporation from overhead systems
3. evaporation from bare soil and water intercepted by the crop
4. evapotranspiration from vegetation which is not the intended crop, or not the harvestable yield, but which is economically used, e.g. for thatch, pasture or medicinal purposes
5. evapotranspiration from vegetation which is not economically used, e.g. weeds

Surface losses

6. canal flow which is not applied to the field
7. runoff from fields
8. outflow from drains

Flows to groundwater

9. seepage losses from canals or pipes
10. seepage losses from fields.

Assessing both the quality and quantity of the listed losses will provide information to assess the efficiency and effectiveness of irrigation at a whole-of-system scale. As is the case with each of the components listed previously (storage, conveyance, distribution and field) the next important step is the definition of the efficiency measure and the elements of the water balance used to derive it.

An important consideration in calculating WUE at a scheme or basin level is whether the system is closed or open. While no water leaves the basin or scheme in a closed system, in an open system useable water does leave the basin or scheme. This concept is important when considering the overall system efficiency. If the system is open then the percentage of the outflow that is beneficially recycled must be included in the calculation of the overall system efficiency.

As indicated earlier, in the Barrett, Purcell & Associates framework, the overall project efficiency is a product of the efficiencies of the field, conveyance and distribution systems. This definition does not directly allow for the capture and reuse of runoff and deep percolation water. In a system that did reuse its water in this way the reused water is subtracted from the water applied and the irrigation efficiency of the whole system could be much higher than individual fields.

In a closed system, where all useable water is captured and allocated, the consumed water can become so polluted that it cannot be used. When a closed system develops, those at the tail-end of the system generally blame those at the top end of the system for problems in the quantity and quality of the supply. It has been noted that as water supplies become more limiting, water basins tend towards closed systems.

Optimising the agronomic factors that may contribute to improved use of water (crop and variety selection, planting date, tillage, fertiliser application and harvest techniques) may conflict with minimising water losses. Maximising rainfall effectiveness and optimising the use of stored soil water may be as important as minimising irrigation losses. Generally though, for a fixed production system, the system with the lowest losses will have the highest water use efficiency. When assessing efficiencies it is not only the physical aspects of the irrigation system that are of concern but also other emergent properties, such as the service industries that develop as a direct result of the presence of the irrigation scheme. Considering these factors adds to the complexity of an already complex problem but highlights the need for a multidisciplinary approach that considers the economic and social aspects as well as the physical.

Adding further to the complexity of the problem is the farmer's view of the success of an irrigation scheme. This view will depend on where in the system they sit and may be very different to the views of the operators of the system. In turn these views may be diametrically opposed to the view of society in general. Therefore an approach is required that tries to avoid formulating a solution from one perspective while excluding all other perspectives.

Measurement

Measuring whole-of-system water use efficiency is conceptually and logistically more difficult than measuring efficiency in any one of the sub-systems. As mentioned previously, losses at one point may not necessarily be a loss in the whole system, as some of the water that is lost will turn up in another location. However the rate of return of these lost flows can vary from a few hours, as with tailwater runoff, to many years, as may be the case when water returns through the groundwater system.

Estimating whole-of-system water use efficiency

Land & Water Australia has commissioned a study to model a whole-of-system water balance, which is being conducted by the NSW Water Use Efficiency Advisory Unit. Bayesian Networks have been employed to help model the complex interactions between different components of the water balance. The project is funded by the National Program for Sustainable Irrigation and is being carried out in consultation with stakeholder groups such as private and public water administrators and irrigators.

Currently water balances for two catchments have been undertaken. It is expected the methods developed from these 'pilot' catchments will be transferred to other catchments. The framework will provide private and public water administrators with a more rigorous methodology for determining where improvements in efficiency can be made.

Regional case study: Angas Bremer

The following case study provided by Tony Thomson, South Australian Department of Water, Land & Biodiversity Conservation, demonstrates a whole-of-system approach to improving irrigation efficiency.

The Angas Bremer district is 60 km southeast of Adelaide and is named after the Angas and the Bremer rivers. It is one of South Australia's premium winegrape regions, growing 5,000 ha of grapes. This region, rich in alluvial soils washed down from the Adelaide Hills, also grows potatoes (500 ha), lucerne hay (400 ha), brussel sprouts and a unique crop of special cane used in the manufacture of reeds for clarinets and other musical instruments.

By 1981 the annual use of groundwater for irrigated agriculture in the Angas Bremer District had increased to four times the annual groundwater recharge. In the 20 years since then groundwater use has been reduced by 80%. Keys to this success have included determined local leadership, teamwork and good communications involving irrigators, their community and specialists from Government agencies.

Both the farmgate income and the area of land irrigated have increased while the volume of irrigation water used has decreased. This was achieved by developing and empowering the community to adopt innovative water management policies. Groundwater licences were exchanged for lakewater licences, locally-funded pipelines were built and crop types changed.

Aquifer over-pumping

In 1981, annual groundwater use had reached 26,600 ML, four times the estimated annual recharge of 6,000 ML. Before the area was proclaimed and managed under the *Water Resources Act*, bore pumps were starting to suck air and irrigators were forced to deepen bores. If irrigators hadn't made dramatic changes, water levels would have continued to drop and salinity would have increased to the point where the water was unsuitable for irrigation.

Leading local irrigators worked closely with specialists from government departments to develop solutions and win community support for tough water management policies, and it is this determination that has resulted in reduced groundwater use. The key to winning the support of all growers was strong leadership and local input in developing and implementing policies.

Increasing aquifer recharge

Individual irrigators have played an important role in changing water use in the district. A system of aquifer storage and recovery was implemented where winter floodwaters were directed into 30 recharge bores. This achieved a maximum annual recharge of more than two thousand megalitres in 1992.

Decreasing groundwater irrigation

Water management policies which reduced groundwater use included cuts of 30% to the volumes of all licences and additional reductions when licences were sold. Because the Angas and Bremer rivers flow into Lake Alexandrina, government approval was won for policies which encouraged conversion from groundwater to lake-water licences. Irrigators who converted to lake-water avoided the 30% cut but incurred increased costs to transport the lower-salinity lake-water to their crops.

In addition to building individually-owned pipelines, one group of irrigators invested in a locally-funded, state-of-the-art, community pipeline scheme to transport water up to 17 km from Lake Alexandrina to their high value crops.

Over the 20-year period, implementing innovative water resource management policies has enabled the Angas Bremer District to double the irrigated area to 6,800 ha, while reducing the combined lake and groundwater irrigation from 26,600 to 17,500 ML.

The combination of astute management policies and a large increase in grape prices in the early 1990s provided the incentives needed for many Angas Bremer irrigators to change from lucerne hay to grapes. Compared with one hectare of lucerne, winegrapes require only one quarter of the water (2.5 ML/ha or 250 mm/yr). Premium quality grapes currently return more than ten times the lucerne farmgate income per megalitre of irrigation water.

Many irrigators have also greatly improved their water management skills and installed monitoring equipment and more efficient water delivery systems, such as centre-pivots.

Irrigation annual reporting

All the Angas Bremer irrigators have, over the past five years, taken part in a simple, low cost process called Irrigation Annual Reporting. Each grower has collected and recorded data including their annual water meter readings and the area of each crop type under irrigation. The data has been collated into district irrigation annual reports and distributed to each grower.

Each year, public meetings and training workshops have been held to present and analyse the information. This irrigation annual reporting has become a valuable educational tool as each year the irrigators can benchmark themselves and compare their practices between years and with other irrigators. The process has made irrigators more aware of what they are doing and of the opportunities to improve.

Reducing drainage: FullStop

It has been acknowledged that the increased use of water imported from Lake Alexandrina, combined with reduced groundwater use, is likely to cause the watertable to rise. Watertables returning even to their pre-1950 levels may adversely affect some recent irrigation developments close to the lake. To combat this problem Angas Bremer irrigators are implementing a number of novel strategies to monitor and manage watertable levels.

One strategy is the use of watertable-monitoring wells. The growers have each contributed $800 to install six-metre-deep wells on their properties. They use the wells to measure watertable levels and record them in their irrigation annual reports.

The irrigators are also installing the latest CSIRO technology, a $30 device called the FullStop, which flags a warning to STOP irrigating as soon as the rootzone depth has become FULL of water. The FullStop has reportedly already resulted in changes to irrigation practices during pilot tests on ten properties over the past year. Some irrigators are now irrigating for half the amount of time they did previously as a result of installing a FullStop. Recently every irrigator has invested $130 to install two FullStop devices at 0.5 and 1.0 m.

Tree planting

Angas Bremer irrigators are enlarging the area of deep-rooted, winter-active vegetation as one part of their management of the watertable. The rootzone of the vegetation will intercept winter floodwaters, help with irrigation drainage and draw water from the watertable. It is a community-initiated vegetation-planting and management program aiming to protect existing red gum swamps and to increase the area of vegetation. The program requires each irrigator to maintain a minimum of two hectares of deep-rooted winter-active vegetation, for every 100 ML of allocated water.

Code of practice

Demands from the public for responsible environmental management are increasing. A code of practice is being implemented in the Angas Bremer District to provide accreditation to growers who are successfully improving their irrigation management. To comply with the code, growers must complete irrigation annual reports, minimise drainage below their rootzones and plant and maintain deep-rooted, winter-active vegetation. Growers who meet the code will be accredited.

The benefits to growers from accreditation are still being developed. Three benefits recognised so far are as follows:

- the right to promote their good environmental management by using a new logo
- the minimisation of data-collection-and-reporting requirements
- automatic compliance with the water module of a new grape growers environmental management system.

Conclusion

The Angas Bremer experience has shown that a seemingly impossible aim (of reducing groundwater use by 80%) can be achieved when people commit themselves to achieving their goal, they combine their resources, they "dream the same dream" and they work together.

New techniques

Roerink *et al.* (1997) used high resolution LANDSAT Thematic Mapper data together with GIS and field data to assess the performance of an irrigation scheme in Argentina. These authors defined a set of irrigation performance indicators and termed them evapotranspiration indicators.

Low cost monthly satellite data available in the public domain have been used in Brazil to calculate monthly actual and potential crop evapotranspiration, soil moisture and biomass growth. Using these data, crop growing conditions are being studied at a range of scales from individual fields through to the scheme level to gain an understanding of the irrigation performance at each of these scales. See Bastiaanssen *et al.* (2001) for a full description of the methods used.

Implementation and adoption

Determining the water balance to calculate water use efficiency at the whole system scale is a relatively new concept and there are limited examples of it being adopted. However, the whole system water balance is an area of increasing interest in Australia, particularly with respect to how the water balance at one scale (e.g. farm) affects the water balance at another scale (e.g. region). Future research is likely to focus on methods to assess the whole-of-system water balance.

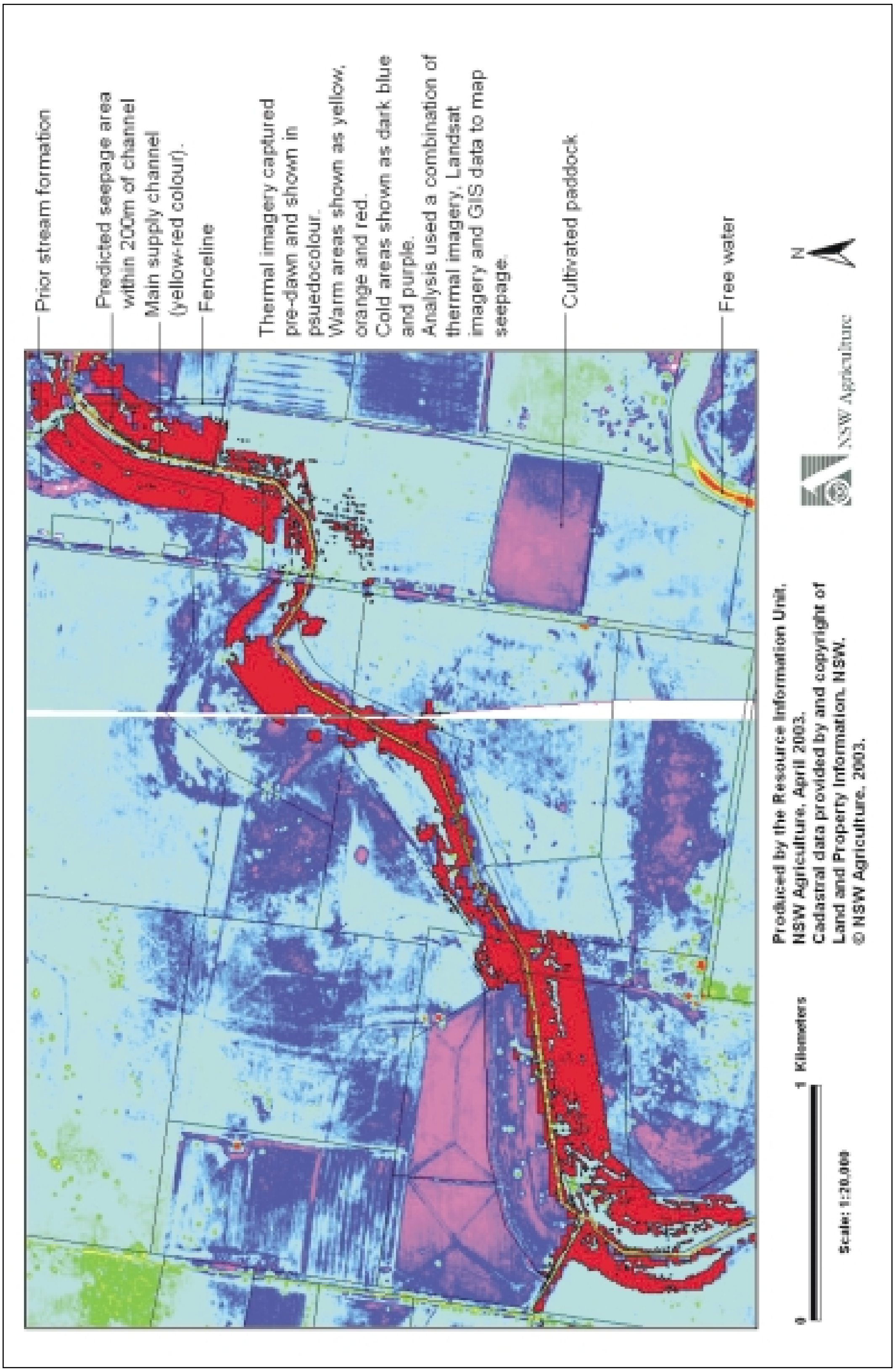
Emerging issues

Salt is continually being moved through leaching and runoff and is further continually being liberated by natural weathering processes and redistributed through irrigation. Therefore, if irrigation efficiencies are improved by reducing the leaching and runoff fractions, the stream transporting the salts will necessarily become more concentrated, which is likely to result in a degraded basin. Therefore it is important to recognise the contribution of the leaching requirement.

Willardson and Wagenet (1983) suggested that the leaching fraction concept should be elevated to the level of a law of water management, which recognises that if salt is in the active hydrologic system and its flow path is to a salt sink (such as the ocean) then it must be allowed to continue along that path. The movement of the salt to the sink may be slowed, but it must be allowed to continue, which requires that some of the water in the river system be explicitly allocated for transporting salt.

There is no unique system or way to manage a system that will result in maximum water use efficiency in all seasons and circumstances; this maximum efficiency is a spatially and temporally dependent function.

Figure 12. Landsat and thermal imagery can be used with GIS data to map areas of seepage.



CHAPTER 7

CONCLUSIONS

There is a considerable volume of literature, spanning a century, on efficiency as it relates to irrigation. This literature encompasses the economic, physical and agronomic aspects of measuring efficiency. There is general consensus in this literature that the water balance is the first requirement to calculate any of the efficiencies defined. Further, there is general consensus on defining the components of the water balance. So why after this century of discussion is there no consensus on a standard method of reporting the efficiency with which water is used in each of the subsystems of an irrigated area?

The answer relates to the difficulties associated with quantifying each of the components of the water balance. These difficulties are compounded by a number of factors, including quality considerations and the temporal and spatial variation of each of the components and the many factors that contribute to that variation.

What is the aim of reporting efficiency? The general perception is, if efficiency is measured and reported, this will identify where water savings can be made and thereby 'free up' water for other uses. However, this is not always the case and herein probably lies the key to the problem, i.e. being able to take a whole system view, rather than considering each potential saving in isolation. Of course, this further compounds the complexity of the initial problem so the next step is to be able to put all the subcomponents back together in a way that captures the complexity of the system but presents the outcomes in an easily interpretable, clear and concise package. This is a tall order!

The level of efficiency that can potentially be attained is not simply the amount of water taken up by a crop compared to the amount of water applied. This concept does not take into account all the factors that contribute to the loss of water in an irrigation system (climate, soil type, hydrology, type of irrigation and topography). These factors are mostly unpredictable and heterogenous and therefore complicate the management and measurement of the system. However, it is important to continue to develop simple methods to enable the required managements at the appropriate scales. Often these simple measurements can lead to improved outcomes through a better understanding of the system and, in turn, can lead to further measurements at different scales. Therefore, it is important that the variables included in the definitions are readily measured.

What is important is that any definition or suite of definitions incorporates an indicative measure of the effective management of the system, rather than simply quantifying efficiency.

APPENDIX

Table 1. International Standards for evaluating irrigation systems.

STANDARD	DESCRIPTION
ISO 11545:2001	Agricultural irrigation equipment - Centre pivot and moving lateral irrigation machines with sprayer or sprinkler nozzles - Determination of uniformity of water distribution
ISO 7714:2000	Agricultural irrigation equipment - Volumetric valves - General requirements and test methods
ISO 7749-1:1995	Agricultural irrigation equipment - Rotating sprinklers - Part 1: Design and operational requirements
ISO 7749-2:1990	Irrigation equipment; rotating sprinklers; part 2: uniformity of distribution and test methods
ISO 8026:1995	Agricultural irrigation equipment - Sprayers - General requirements and test methods
ISO 8026:1995/Amd 1:2000	Agricultural irrigation equipment - Sprayers - General requirements and test methods
ISO 8224-1:1985	Traveller irrigation machines; Part 1 : Laboratory and field test methods
ISO 8796:1989	Polyethylene (PE) 25 pipes for irrigation laterals; susceptibility to envi ronmental stress-cracking induced by insert-type fittings; test method and specification
ISO 9260:1991	Agricultural irrigation equipment; emitters; specification and test methods
ISO 9261:1991	Agricultural irrigation equipment; emitting-pipe systems; specification and test methods
ISO 9644:1993	Agricultural irrigation equipment; pressure losses in irrigation valves; test method

Table 2. Examples of Water Use Indices from Australian Literature.

CROP	IRRIGATION METHOD	EFFICIENCY/INDEX NAME	EFFICIENCY/INDEX RATIO	Units	EFFICIENCY/INDEX VALUE AVERAGE	MINIMUM	MAXIMUM
Cereal crops	unknown	Farm Total WUI	Yield / (Rainfall + Irrigation)	kg / mm		2.9	5
citrus	spray	Irrigation Economic WUI	Gross return / Irrigation Volume	$ / ML	2118	856	3491
citrus	spray	Irrigation WUI	weighted yield / Irrigation Volume	t / ML	6.2	4.3	8
citrus	drip	Irrigation WUI	weighted yield / Irrigation Volume	t / ML	17	0.7	17
citrus	spray	Irrigation WUI	Yield / Irrigation Volume	t / ML	5.6	2.8	10.3
citrus	spray	Yield per Drainage Volume WUI	Yield / Drainage Volume	t / ML	70.0	8.7	136.5
cotton	surface	Crop WUI	Yield / seasonal ET	bales / ML	1.0	0.9	1.2
cotton	surface	Crop WUI	Yield / Irrigation Volume	kg / mm	1.5	1.0	2.4
cotton	surface	Farm irrigation WUI	Yield / (Rainfall + Irrigation)	bales / ML	1.2	0.4	2.5
cotton	surface	Farm Total WUI	Yield / (Irrigation + Storage + Effective Rainfall + soil moisture)	bales / ML	0.8	0.4	1.0

CROP	IRRIGATION METHOD	EFFICIENCY/INDEX NAME	EFFICIENCY/INDEX RATIO	UNITS	EFFICIENCY/INDEX VALUE AVERAGE	MINIMUM	MAXIMUM
cotton	drip	Farm Total WUI	= Yield / (Irrigation Water Applied + Effective Rainfall + Antecedent Soil Water)	kg / mm	2.2	1.5	2.8
cotton	surface	Farm Total WUI	= Yield / (Irrigation Water Applied + Effective Rainfall + Antecedent Soil Water)	kg / mm	2.3	1.9	2.5
cotton	surface	Farm Total WUI	= Yield / (Rainfall + Irrigation)	bales / ML	0.8		
cotton	surface	Irrigation WUI	= Yield / Irrigation Volume	bales / ML	1.0	0.6	1.5
cotton	surface	Irrigation WUI	= Yield / Irrigation Water Applied	kg / mm	5.1	2.5	18.2
cotton	drip	Irrigation WUI	= Yield / Irrigation Water Applied	kg / mm	5.6	2.5	13.9
dairy	surface	Farm Total WUI	= Volume of Product (milk fat + protein) / (Irrigation + Effective Rainfall)	kg / ML	64	35	94
dairy	surface	Farm Total WUI	= Volume of Product (milk) / (Irrigation + Effective Rainfall)	kg / ML	884	498	1287
Faba Bean	unknown	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm		8.7	14.3
Field pea	unknown	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm		13.3	28.6
Hairy vetch	unknown	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm		3.8	6.1

Table 2. Examples of Water Use Indices from Australian Literature.

CROP	IRRIGATION METHOD	EFFICIENCY/INDEX NAME	EFFICIENCY/INDEX RATIO	Units	EFFICIENCY/INDEX VALUE AVERAGE	MINIMUM	MAXIMUM
Lablab	surface	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm	51		
Lucerne	unknown	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm		1.8	22.4
Lucerne	surface	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm	18.3		
Lupin	unknown	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm		31	58
Rapeseed	unknown	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm		33	58
Soybean	unknown	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm		4.8	9
Soybean	surface	Farm Total WUI	= Yield / (Rainfall + Irrigation + Change in Soil Water Store)	kg / mm	3.7	3	5
Soybean	surface	Irrigation WUI	= Yield / Irrigation Volume	t / ML	10.3	6	16
Subterranean clover	unknown	Farm Total WUI	= Yield / (Rainfall + Irrigation)	kg / mm		4.8	20.5
Sugar Cane	surface	Farm Total WUI	= Yield / (Irrigation+ Effective Rainfall)	t / ML	7.3	4.5	10
Sugar Cane	surface	Irrigation WUI	= Yield / Irrigation Volume	t / ML	5.9	4.9	6.9

Table 3. Examples of Water Use Efficiencies from Australian Literature.

CROP	IRRIGATION METHOD	EFFICIENCY/INDEX NAME	EFFICIENCY/INDEX RATIO	EFFICIENCY/INDEX VALUE AVERAGE	MINIMUM	MAXIMUM
citrus	drip	Field Application Efficiency	= (Irrigation Volume - Drainage Volume (ML)) / (Irrigation Volume (ML)) X 100 =	96	65	96
citrus	spray	Field Application Efficiency	= (Irrigation Volume - Drainage Volume (ML)) / (Irrigation Volume (ML)) X 100 =	85	66	96
cotton	surface	Farm Irrigation WUE	= (Irrigation water used in ET (ML)) / (Irrigation Volume (ML)) X 100 =	59	28	80
cotton	surface	Farm Total WUE	= (ET + Change in soil water (mm)) / (Stored Water + Irrigation + Effective Rainfall (mm)) X 100 =	76	75	77
cotton	surface	Farm Total WUE	= (seasonal ET (mm)) / (Rainfall + Irrigation (mm)) X 100 =	75	53	92
cotton	surface	Farm Total WUE	= (seasonal ET (ML)) / (Total seasonal water usage (ML)) X 100 =	70	33	90
cotton	surface	Field Application Efficiency	= (Irrigation Volume - Runoff (ML)) / (Irrigation Volume (ML)) X 100 =	85	74	89
Sugar Cane	surface	Distribution Uniformity	= (average infiltrated depth in the least-irrigated 25% of the field (mm)) / (average infiltrated depth over the whole field (mm)) X 100 =	91	84	97
Sugar Cane	surface	Field Application Efficiency	= (Readily Available Water (RAW) (mm)) / (Irrigation Water Applied (mm)) X 100 =	51	13	95
Sugar Cane	surface	Field Application Efficiency	= (volume of water per furrow spacing stored in the rootzone (ML)) / (Irrigation Volume (ML)) X 100 =	76	58	93

References consulted for the WUIs and WUEs ratios reported in Appendix, tables 2 and 3.

1. Skewes, M. A. (1997) Technology Vs management skill – the Challenge of Efficient Irrigation. *Striking the Balance: Irrigation and the Environment – the 44th Annual ANCID Conference and Study Tour*, Deniliquin, NSW.
2. Douglass, W. and Poulton, D. (2000) Living With Limited Water - Towards Efficient Water Use on Irrigated Dairy Pastures. ICID Journal 49(2), 29-40.
3. Armstrong, D. P., Knee, J. E., Doyle, P. T., Pritchard, K. E., and Gyles, O. A. (2000) Water-use efficiency on irrigated dairy farms in northern Victoria and southern New South Wales. *Australian Journal of Experimental Agriculture* 40(5), 643-653.
4. Cull, P., George, B., and Finney, B. (1985) *Whole farm irrigation efficiency and water management for the 1984/85 cotton crop at Moree*. IAA.
5. Holden, J. R. and Mallon, K. M. (1997) *Increasing Irrigation Efficiencies in the Australian Sugar Industry*. Queensland Bureau of Sugar Experiment Stations. Research and Development Final Report (Land and Water Resources Research and Development Corporation).
6. Hodgson, A. S, Constable, G. A, Duddy G.R, and Daniells I.G. (1990) A comparison of drip and furrow irrigated cotton on a cracking clay soil - 2. Water use efficiency, waterlogging, root distribution and soil structure. *Irrigation Science* 11(3), 143-148.
7. Keefer, G. D., Yule, D. F., Ladewig, J. H., and Nickson, D. J. (1985) Improving irrigation efficiency in a semi arid subtropical environment, A: Cotton yields and water use efficiency. *In Crop and Pasture Production: Science and Practice*. Australian Agronomy Conference, University of Tasmania, Jan-Feb 292.
8. Mason, W. K., Constable, G. A., and Smith, R. C. G. (1980) Irrigation for crops in a subhumid environment II. The water requirements of soybeans. *Irrigation Science* 2(1), 13-22.
9. MacDonald, L. M., Wright, P, and MacLeod, D. A. (2001) Nitrogen fixation by lablab (Lablab purpureus) and lucerne (Medicago sativa) rotation crops in an irrigated cotton farming system. *Australian Journal of Experimental Agriculture* 41(2), 219-225
10. Raine, S., Bakker, D., and Robertson, M. (1997) Alternate furrow irrigation improves water use efficiency. *Australian Sugarcane* 1(4), 6-7. 97. Sugar Research and Development.
11. Raine, S. and Walker, W. R. (1998) Improving the efficiency of surface irrigation. *Leading Edge*, 37-39.
12. Skewes, M. A. and Meissner, T. (1997) *Irrigation Benchmarks and Best Management Practices for Citrus*. South Australia, Primary Industries and Resources SA.
13. Tennakoon, S. B. and Milroy, S. P. (1999) Evaluation of crop water use efficiency and farm level irrigation efficiency of irrigated cotton farms in Northern NSW and Southern Queensland. *Proceedings of the Cropping Systems Forum*.
14. Hearn, B., Cameron, J., and Jackson, B. (1997) Water use efficiency: If you don't measure it you can't manage it! *The Australian Cottongrower*.

Table 4. R&D groups involved in WUE and current research *(thanks to David Williams for his help in compiling this table).*

R & D GROUPS INVOLVED IN IRRIGATION RELATED WUE	RESEARCH AREA
Australian National Committee on Irrigation and Drainage (ANCID) www.ancid.org.au	Open channel seepage and control Metering - Know the Flow Benchmarking Australian water providers
Charles Sturt University, Wagga Wagga, NSW www.csu.edu.au/faculty/sciagr/sag/home www.csu.edu.au/student/newagriculture	Irrigation systems conversions Education and training on irrigation technology Use of Polyacrylamides (PAM) Prediction of salinity trends in irrigation areas Crop establishment with sub-surface drip irrigation Implication of policy changes on WUE Partial rootzone drying and regulated deficit irrigation National Irrigation Education Initiative
National Wine and Grape Industry Centre www.csu.edu.au/nwgic	Nutrition and irrigation strategies to minimise vineyard inputs, reduce environmental impact and improve grape quality Shiraz berry shrinkage Improved water use efficiency for irrigated vines The water economy of the grape berry
CRC for Viticulture www.crcv.com.au	Water Use Efficiency: Matching Rootstocks and Scions Partial Rootzone Drying and Wine Grape Quality Water Use Efficiency: Application of isotope discrimi nation techniques Hormonal Control of Water Use and Berry Ripening VineLOGIC Education Package CRCV Viticulture Research to Practice® - Water Management for Grape Production Encouraging grower adoption of improved irrigation practices WUE through partial rootzone drying and understand ing the role of abscisic acid in grapes Identifying water use efficient grape varieties Improved vine irrigation through computer simulation Identifying best management practices for irrigation management in vineyards
CRC for Catchment Hydrology www.catchment.crc.org.au	Catchment hydrology modelling Catchment behaviour models linking hydrologic, pollu tant-transport, ecologic, geomorphic, meteorologic and socio-economic aspects Modelling approaches that utilise latest data-integra tion technology Sustainable water allocation
CRC for Cotton www.cotton.crc.org.au	Improving on farm irrigation water use efficiency in the Queensland cotton and grain industries Hydrologic modelling to develop sustainable irrigation management practices in cotton production

Table 4. R&D groups involved in WUE and current research (*continued*).

R & D GROUPS INVOLVED IN IRRIGATION RELATED WUE	RESEARCH AREA
Cotton Research and Development Corporation (CRDC) www.crdc.com.au	Assessing water use efficiency on eastern Australian Cotton farms Improving understanding of cotton water use for better management in water limited environments Best management practice for maximising whole farm irri gation efficiency in the Australian cotton industry
CRC for Sustainable Rice Production www.ricecrc.org.au	Study of water use and environmental aspects of rice growing Rice water use efficiency workshop proceedings Measurement of losses from on-farm channels and drains A farm scale hydrologic economic optimisation model to manage waterlogging and salinity in irrigation areas Reduction of the gap between crop water use efficiency and theoretical requirement Monitoring, evaluating and predicting the state of natural resources in irrigated rice regions Development of technologies for increased water use efficiency on irrigation rice farms Development of a Decision Support System for evaluating seepage from on-farm channels and drains Development of rice cultural systems with higher water use efficiency Use of remote sensing to monitor attributes of the irrigation system Development of farm, irrigation and catchment scale models for optimal management of irrigation systems and evaluation of alternative production systems
CRC for Sustainable Sugar Production www-sugar.jcu.edu.au	Making best use of limited water in sugarcane production systems Improving sugarcane quality for better water management WUE in sugarcane on shallow watertables in Northern Australia Irrigation salinity in sugarcane areas Irrigation water pricing in sugarcane areas
CSIRO	Benchmarking whole cotton farm water use efficiency to assist in identifying opportunities to improve farm design and irrigation management WUE and groundwater impacts in Northern Australia Irrigation salinity Simple soil moisture monitoring techniques Improving WUE in sugarcane Irrigation water pricing Evaluating WUE and improving irrigation scheduling using crop simulation models Partial rootzone drying in grapes, citrus and pome fruit Resource management for sustainable irrigated agriculture Conversion to micro-irrigation systems in the Griffith area of NSW Rigorously determined water balance benchmarks for irri gated crops and pastures Improving the water use efficiency of horticultural crops Improving irrigation scheduling for crops underlain by shal low, fresh watertables

Table 4. R&D groups involved in WUE and current research (*continued)*.

R & D GROUPS INVOLVED IN IRRIGATION RELATED WUE	RESEARCH AREA
Department of Agriculture, Western Australia www.agric.wa.gov.au	Irrigation system design
Department of Natural Resources and Environment, Vic www.nre.vic.gov.au	WUE on Irrigated Dairy Farms, Northern Vic Irrigation system selection using Bayesian Networks Encouraging grower adoption of improved irrigation practices Water use efficiency in north-west Victorian grain crops Water Use Efficiency in Fruit Trees through Partial Rootzone Drying Increasing Water Use Efficiency Through Improved Irrigation System Design Improved Orchard Productivity and Water Use Efficiency using Modern Irrigation and Tree Management Techniques Increasing the Impact of Research and Extension in Irrigated Agriculture Improved irrigation practices for forage production
Department of Primary Industries, Queensland www.dpi.qld.gov.au	WUE reductions under sub-surface drip on lucerne in Qld WUE in the sugar Qld sugar industry WUE of pasture and crop species in a sub-tropical environment Improving WUE in sugarcane Encouraging grower adoption of improved irrigation practices
Department of Natural Resources, Queensland www.nrm.qld.gov.au	Irrigation evaluation Mitigating evaporative losses Sustainable turf irrigation management strategies Rural Water Use Efficiency Initiative Water Use Efficiency Discussion List Water efficient forage production in the subtropical dairy systems for improved profitability and environmental sustainability Increased profitability and water use efficiency through best use of limited water under supplementary irrigation Development of measurement and diagnostic "toolkits" to evaluate and improve the performance of sprinkler irrigation systems Investigation of in-field irrigation management practices that improve irrigation efficiency of furrow irrigated cotton production systems Management of furrow irrigation to improve water use efficiency and sustain the groundwater resource: a case study in the Burdekin region Trickle Irrigation on heavy clay soils: an opportunity to increase water use efficiency and reduce off farm environmental impacts Quantifying high priority reasons for vegetable producers to adopt improved irrigation management strategies Sustainable horticultural irrigation project Assessment of irrigation strategies for the best use of limited water: a review of relevant irrigation research to date Short term climate forecasting and risk management to improve irrigation scheduling and improve water use efficiency

Table 4. R&D groups involved in WUE and current research (*continued*).

R & D GROUPS INVOLVED IN IRRIGATION RELATED WUE	RESEARCH AREA
GRDC www.grdc.com.au	Deep drainage on clay soils in Qld and NSW What do we know about irrigation system performance
Murray-Darling Basin Commission www.mdbc.gov.au	Water use decision support framework Best management practices for irrigated dairying Adoption of irrigation best practices for vegetables in the Southern Murray-Darling Basin Best management practices for improved WUE for irrigated vines Quantification and remediation of channel seepage Environmental stewardship in irrigated agriculture Development of an irrigation management and information reporting system in the Murray-Darling Basin Sustainable groundwater use within irrigated catchments Guidelines for land use suitability and capability for irrigation planning and development Delivering improved WUE across the Murray-Darling Basin Developing Decision Support Systems for improving WUE in the northern Murray-Darling Basin Irrigation water use decision support framework Development of a framework for WUE policies and actions
Land and Water Australia www.lwa.gov.au National Program for Sustainable Irrigation	Development of guidelines for Quantification and Monitoring of Seepage from Earthen Channels Gaining an acceptance of Water Use Efficiencies framework, terms and definitions
National Centre for Engineering in Agriculture (University of Southern Queensland & Qld Natural Resources and Mines) www.ncea.org.au	An evaluation of the efficiency and practical efficacy of a range of commercially available farm dam evaporation control products Development of information and training resources for the Qld horticultural industry Development of measurement and diagnostic "toolkits" to evaluate and improve the performance of sprinkler irrigation systems Audit of Water and Irrigation use Efficiencies on farms within the Queensland horticultural industry Technical support for the QFVG "Water for Profit" adoption program Working towards water use efficient irrigation management systems in the Qld Murray-Darling Basin Partial rootzone drying and regulated deficit irrigation for cotton using large mobile irrigation machines Investigation of in-field irrigation management practices that improve irrigation efficiency of furrow irrigated cotton production systems A simulation, calibration and optimisation model for the design and management of surface irrigation Demonstration model of sustainable effluent irrigation for golf courses Irrigation extension activities within a best management practices framework Irrigation evaluation methods and models

Table 4. R&D groups involved in WUE and current research (*continued*).

R & D GROUPS INVOLVED IN IRRIGATION RELATED WUE	RESEARCH AREA
	Extent of efficient irrigation technology in the Australian cotton industry Maximising irrigation efficiency in the Australian cotton industry Implementing efficient on farm water use practices Optimisation of surface drainage design with demonstration and adoption in low lying Canelands Research, Development and Extension in Irrigation and Water Use Efficiency - A review for the Rural Water Use Efficiency Initiative A water use study in the Dairy Industry Evaluating On-farm water use efficiency in the Mary River catchment Furrow Irrigation Design Optimiser
NSW Agriculture www.agric.nsw.gov.au	Determining 'whole of system' water use efficiencies for NSW river valleys Irrigation best practices for vegetables in the southern Murray-Darling Basin, 1998 - 2002 Channel seepage Soil moisture monitoring and irrigation scheduling Irrigation evaluation Evaluating WUE using crop simulation models Soil management for irrigated areas
Ord Irrigation Co-operative	Increasing WUE in the Ord
Primary Industries and Resources South Australia	Calculating irrigation requirements
The University of Queensland (UQ) www.uq.edu.au	Irrigation water pricing
The University of Sydney www.usyd.edu.au	Subsurface irrigation Mapping deep drainage under irrigation in the Gwydir and Macquarie valleys
University of Melbourne www.unimelb.edu.au	Urban tree irrigation
University of New England www.une.edu.au	Encouraging grower adoption of improved irrigation practices
University of Technology, Sydney www.uts.edu.au	Groundwater Computer Software
University of Western Australia www.uwa.edu.au	Water relations and ecophysiology of Eucalyptus marginate (Jarrah) in mine site rehabilitation
University of New South Wales www.unsw.edu.au	Irrigation salinity Irrigation impacts on groundwater Arsenic cycling risks in irrigation on coastal aquifers

BIBLIOGRAPHY

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998) Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. *FAO Irrigation and Drainage Paper 56.*

Allen, R. G. and Willardson, L. S. (1997) Water use definitions for defining hydrologic impacts of water conservation. *Proc* ICID Workshop - Sustainable Irrigation in Areas of Water Scarcity and Drought. 11-12 September, Oxford, England.

ANCID (Australian National Committee on Irrigation and Drainage) (2001) Open channel seepage and control. Vol 2.1 Literature review of earthen channel seepage remediation techniques. Australian National Committee on Irrigation and Drainage, www.ancid.org.au

ANCID (Australian National Committee on Irrigation and Drainage) (2002) *Australian Irrigation Water Provider Benchmarking Report.* Land and Water Australia, Murray Darling Basin commission and Agriculture, Fisheries and Forestry – Australia, www.ancid.org.au

AS (Australian Standard) 1289 (2000) Methods of Testing Soils for Engineering Purposes - General requirements and list of methods. Standards Australia.

Australian Science and Technology Heritage Centre (2000) Technology in Australia. [Online]. Available at: http://www.austehc.unimelb.edu.au/tia/ [2002, August 6]

Australian Water Resources Assessment (2000) Surface water and groundwater - availability and quality [Online]. Available at:
http://audit.ea.gov.au/ANRA/water/docs/national/Water_Contents.html [2002, August 6].

Bakker, D. M., Raine, S. R. and Robertson, M. T. (1997) A preliminary investigation of alternate furrow irrigation for sugar cane production. *Proceedings of the Australian Society of Sugar Cane Technology 19th Conference*. Cairns, Qld.

Banyard, R. (1983) Ord Irrigation area Ivanhoe Plain waterway infiltration. Water Resource Branch, Engineering Division Public Works Department, Western Australia, Report No. W.R.B. 57.

Barrett Purcell & Associates (1999) Determining a framework, terms and definitions for water use efficiency in irrigation. Report to Land and Water Resources Research and Development Corporation, September 1999. 26p. Land & Water Australia, www.lwa.gov.au

Bastiaanssen, W. G. M; Brito R.A.L., Bos M.G., Souza R.A., Cavalcanti E.B., Bakker M.M. (2001) Low cost satellite data for monthly irrigation performance monitoring: benchmarks from Nilo Coelho, Brazil. Irrigation and Drainage Systems, Kluwer Academic Publishers, Dordrecht, 15(1): 53-79.

Blair, A. W. and Smerdon, E. T. (1988) Unimodal surface irrigation efficiency. *Journal of Irrigation and Drainage Engineering*. 114:156-168.

Bos, M. G. (1985) Summary of ICID definitions on irrigation efficiency. ICID Bulletin 34: 28-31

Bos, M. G. and Wolters, W. (1989) Project or overall irrigation efficiency. In *Irrigation: Theory and Practice.* eds. J. R. Rydzewski, and C. F. Ward, 499-506. Proceedings of the International Conference held at the University of Southampton, 12-15 September, London, UK: Pentech Press.

Boughton, W. (1999) *A Century of Water Resources Development in Australia, 1900-1999.* The Institution of Engineers, Australia.

Bouwer, H., Nakayama, F. S., Reginato, R. J., and Replogle, J. A. (1984) Conserving water in irrigation. *Proceedings of NWWA Western Regional Conference on Ground Water Management.* San Diego, California. Worthington, OH: National Water Well Association. 59-66.

Brown, G. (2002) Investigation into the Practicality of and Potential for Controlling Evaporation Losses from On-Farm Storages, DPI, Toowoomba

Brown, H. (1920) *Irrigation, its Principles and Practice, as a Branch of Engineering*. 3rd edition. London England. 32p.

Browne, R. (1982) How to cut water loss. *Australian Country*. 26:52-59.

Burt, C. M., Clemmens, A. J., Strelkoff, T. S., Solomon, K. H., Bliesner, R. D., Hardy, L. A., Howell, T. A. and Eisenhauer, D. E. (1997) Irrigation performance measures: efficiency and uniformity. *Journal of Irrigation and Drainage Engineering*. 123:423-442.

Burt, C. M. (1999) Irrigation water balance fundamentals. *Proceedings of the USCID Water Management Conference*, 10-13 March, San Luis Obispo, CA.

Burt, C. M. & Piao, X. (2002) Advances in PLC-based canal automation. *Proceedings of the USCID conference on Benchmarking Irrigation System Performance Using Water Measurement and Water Balances.* 9-12 July, San Luis Obispo, CA.

Carter, R., Kay, M. and Weatherhead, K. (1999) Water losses in smallholder irrigation schemes. *Agricultural Water Management*. 40: 15-24.

Charlesworth, P. (2000) Soil water monitoring. *Irrigation Insights, Number 1*. National Program for Irrigation Research and Development. www.lwa.gov.au

Christiansen, J. E. (1942) Irrigation by sprinkling. *California Agricultural Experiment Station Bulletin 670*, University of California, Berkeley, CA.

Clemmens, A. J. and Bos, M. G. (1990) Statistical methods for irrigation system water delivery performance evaluation. *Irrigation and Drainage Systems*. 4: 345-365.

Clemmens, A. J. and Dedrick, A. R. (1984) Irrigation water delivery performance. *Journal of Irrigation and Drainage Engineering*. 110:1-13.

Clemmens, A. J and Solomon, K. H. (1997) Estimation of global irrigation distribution uniformity. *Journal of Irrigation and Drainage Engineering*. 123(6):454-461.

Clemmens, A. J. (1999) How accurate are irrigation performance estimates. *Proceedings of the USCID Water Management Conference,* 10-13 March, San Luis Obispo, CA.

Dalton, P., Raine, S. and Broadfoot, K. (2001). Best management practices for maximising whole farm irrigation efficiency in the cotton industry. Final Report for CRDC Project NEC2C. National Centre for Engineering in Agriculture Publication 179707/2, USQ, Toowoomba.

DLWC (Department of Land and Water Conservation) (2002) Building a farm dam. [Online]. Available at: http://www.dlwc.nsw.gov.au/care/soil/soil_pubs/pdfs/building_a_farm_dam.pdf [2002, October 28]

Douglass, W., and Poulton, D. (2000) Living with limited water – towards efficient water use on irrigated dairy pastures. *ICID Journal*. 49:29-40.

Dry, P.R., Loveys, B.R., Stoll, M., Stewart, D., and McCarthy, M.G. (2000) Partial rootzone drying - an update. *Australian Grapegrower and Winemaker.* 438a: 35-39

Fernandez, C. J., Tewolde, H., Elledge, R., Camp, C. R., Sadler, E. J., and Yoder, R. E. (1996) Deficit-irrigation strategies for cotton in semiarid southwest Texas. *Evapotranspiration and Irrigation Scheduling. Proceedings of the International Conference, Texas, USA*. November 3-6. 1151-1156

Fortier, S. (1928) Irrigation requirements of the arid and semi-arid lands of the Missouri and Arkansas river basins. *USDA Technical Bulletin No 36.* Washington DC 112p.

Gencoglan, C. and Yazar, A. (1999) The effects of deficit irrigation on maize yield and water use efficiency. *Turkish Journal of Agriculture and Forestry*. 23:233-24.

Graterol, Y. E., Eisenhauer, D. E., and Elmore, R. W. (1993) Alternate-furrow irrigation for soybean production. Journal *Agricultural water management.* 24:133-145

Griffiths, L. (ed.) (1999) Science for a sustainable future. [Online]. Available at: http://www.clw.csiro.au/publications/clw_corporate_profile.pdf [2002, August 6] CSIRO Land and Water Communication Group.

Gutteridge Haskins and Davey Pty Ltd (2001) SWP Distribution System Efficiency Reviews. [Online]. Available at: http://www.nrm.qld.gov.au/rwue/ [2003, January 13].

Hall, W. A. (1960) Performance parameters of irrigation systems. *Transactions of the ASAE* 3(1):75-76, 81.

Hall, W. A. (1960) Performance parameters of irrigation systems. *Transactions of the ASAE* 3(1):75-76, 81.

Hallows, P. J. and Thompson, D. G. (1995) *The History of Irrigation in Australia.* Australian National Committee on Irrigation and Drainage.

Hansard (2000). South Australia Legislative Council, Thursday 13 July. [Online]. Available at: http://www.parliament.sa.gov.au/hansard/2000/lc/wh130700.lc.pdf [2002, August 8]. 1684-1685.

Hansen, V. E. (1960) New concepts in irrigation efficiency. *Transactions of the ASAE* 1960: 55-64.

Hart, W. E. and Reynolds, W. N. (1965) Analytical design of sprinkler systems. *Transactions of the ASAE*. 8:83-85, 89.

Heermann, D. F., Wallender, W. W. and Bos, M. G. (1990) Irrigation efficiency and uniformity. In *Management of Farm Irrigation Systems.* American Society of Agricultural Engineers, St. Joseph, Mi. 125-149.

Hodgson, A. S., Constable, G. A., Duddy, G. R., and Daniells, I. G. (1990) A comparison of drip and furrow irrigated cotton on a cracking clay soil. 2. Water use efficiency, waterlogging, root distribution and soil structure. *Irrigation Science*. 11:143-148.

Holland, G. (1997) Analysis of channel seepage in the Shepparton irrigation region using a geographic information system. Goulburn-Murray Water Corporation, Tatura.

Howell, T. A. (2001) Enhancing water use efficiency in irrigated agriculture. *Agron. J* 93:281-289.

IAG (Independent Audit Group) (1996) Setting the Cap. Independent Audit Group report to the Murray-Darling Basin Ministerial Council, Canberra ACT.

Israelsen, O. W. (1932) *Irrigation Principles and Practices.* Wiley and Sons, New York. 411 pp.

Keefer, G. D., Yule, D. F., Ladewig, J. H., and Nickson, D. J. (1985) Improving irrigation efficiency in a semi arid subtropical environment, A: Cotton yields and water use efficiency. In *Crop and Pasture Production: Science and Practice, Australian Agronomy Conference.* University of Tasmania, Jan-Feb. 292.

Krinner, W., Garcia, A., and Estrada, F. (1994) Method for estimating efficiency in Spanish irrigation systems. *Journal of Irrigation and Drainage Engineering* 120:979-986.

Letey, J. (1985) Irrigation uniformity as related to optimum crop production - additional research is needed. *Irrigation Science*. 6:253-263

Malano, H.M., Turral, H.N. and Wood, M.L. (1996) Surface irrigation management in real time in southeastern Australia: Irrigation scheduling and field application. *in Irrigation Scheduling: From Theory to Practice – Proceedings*. [Online]. Available at: http://www.fao.org/docrep/W4367E/w4367e00.htm#Contents [2002, August 9].

Marshall, P. and Bowman, A (2000) Irrigation Area rehabilitation - Two case studies, Burdekin River, QLD and Loxton, SA, ANCID conference, Toowoomba, QLD.

McCarthy, M. G. (1998) Irrigation management to improve winegrape quality – nearly 10 years on. *The Australian Grapegrower & Winemaker*. Annual Technical Issue:65-71.

MDBMC (Murray-Darling Basin Ministerial Council) (1995) An audit of water use in the Murray-Darling Basin. Murray-Darling Basin Ministerial Council, Canberra ACT.

Merriam, J. L. and Keller, J. (1978) *Farm Irrigation System Evaluation: A Guide for Management.* Department of Agricultural Engineering, Utah State University, Logan, Utah. USA.

Mitchell, D. Development of a whole of system approach to water use efficiency. In *Irrigation: Conservation or Conflict? Proceedings of The Irrigation Association of Australia 2002 National Conference and Exhibition.* Sydney Convention and Exhibition Centre, May 21-23. 23:31

Molden, D. J. and Gates, T. K. (1990) Performance measures for evaluation of irrigation water delivery systems. *Journal of Irrigation and Drainage Engineering*. 116:804-822.

Moustafa, M. M.; Ibrahim, K. A., and Salama, M. M. (1996) Effects of irrigation delivery system improvements on drainage water. Sustainability of irrigated agriculture - irrigation planning and management: measures in harmony with the environment. *Transactions of the 16th*

International Congress on Irrigation and Drainage. Cairo, Egypt. International Commission on Irrigation and Drainage. 11-28.

NLWRA (National Land & Water Resources Audit) (2001). Australian Water Resources Assessment 2000. Natural Heritage Trust.

Omezzine, A. and Zaibet, L. (1998) Management of modern irrigation systems in Oman: allocative vs. irrigation efficiency. *Agricultural Water Management*. 37:99-107.

Penman, H. L. (1963) Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London*. A193:120-146.

Raine, S., Bakker, D., and Robertson, M. (1997) Alternate furrow irrigation improves water use efficiency. *Australian Sugarcane*. 1: 6-7.

Raine, S. R. (ed) (1999) *Research, development and extension in irrigation and water use efficiency: A review for the Rural Water Use Efficiency Initiative*. National Centre for Engineering in Agriculture Publication 179743/2, USQ, Toowoomba.

Rijo, M. and Pereira, L. S. (1987) Measuring conveyance efficiencies to improve irrigation water management. *Irrigation and Drainage Systems*. 3:267-276.

SA Budget Paper (1999) Portfolio – Primary Industries and Resources. [On-line]. Available at: http://www.treasury.sa.gov.au/budg99/cworks/cwpir.pdf [2002, August 8]

Schneider, A. D., Buchleiter G., and Kincaid, D. C. (2000) LEPA irrigation developments. *National irrigation symposium. Proceedings of the 4th Decennial Symposium, Phoenix, Arizona, USA.* 89-96.

Seckler, D. n.d. *Revisiting the "IWMI Paradigm:" Increasing the efficiency and productivity of water use.* Colombo, Sri Lanka: International Water Management Institute.

Skewes, M. A. (1997) Technology vs management skill – the challenge of efficient irrigation. *Striking the Balance: Irrigation and the Environment – the 44th Annual ANCID Conference and Study Tour.* Deniliquin, NSW, ANICD, Australia.

Small, L. E. and Svendsen, M. (1990) A framework for assessing irrigation performance. *Irrigation and Drainage Systems*. 4:283-312.

Smith, D. I. (1998) *Water in Australia: resources and management*. Oxford University Press, Oxford, 384 pp.

Solomon, K. H. (1984) Yield related interpretations of irrigation uniformity and efficiency measures. *Irrigation Science*. 5:161-172.

Solomon, K. H. (1993) Irrigation systems and water application efficiencies. *Irrigation Australia*, Autumn. 6-11.

Solomon, K. H. and Burt, C. M. (1997) Irrigation sagacity: a performance parameter for reasonable and beneficial use. *ASAE Paper No. 97-2181.*

Stephens, W. and Hess, T. (1999) Systems approach to water management. *Agricultural Water Management.* 40: 3-13.

Stirzaker, R. (1999) The problem of irrigated horticulture: matching the biophysical efficiency with the economic efficiency. *Agroforestry Systems*. 45: 187-202.

Stirzaker, R. (2002) Four lessons from a wetting front detector. In *Irrigation: Conservation or Conflict? Proceedings of The Irrigation Association of Australia 2002 National Conference and Exhibition.* Sydney Convention and Exhibition Centre, May 21-23. 245-250.

Triantafilis, J. (2000) Understanding the salinity threat in the irrigated cotton growing areas of Australia. The Australian Cotton Grower, Toowoomba Queensland, May-Jun. pp. 58-60.

Walker, W. R. and Skogerboe, G. V. 1987. *Surface Irrigation Theory and Practice*. Prentice-Hall, NJ.

Wallace, J. S. and Batchelor, C. H. (1997) Managing water resources for crop production. *Philosophical Transactions of the Royal Society of London.* 352:937-947.

Whittlesey, N. K., McNeal, B. L., and Obersinner, V. F. (1986) Concepts affecting irrigation management. *Energy and Water Management in Western Irrigated Agriculture. Studies in Water Policy and Management No. 7*. 101-127.

Willardson, L. S. (1972) Attainable irrigation efficiencies. *Journal of Irrigation and Drainage*. 98:329-246.

Willardson, L. S. and Wagenet, R. J. (1983) Basin-wide impacts of irrigation efficiency. Advances in irrigation and drainage: surviving external pressures. ASCE conference paper, New York.

Wolters, W. and Bos, M. G. (1989) Irrigation performance assessment and irrigation efficiency. International Institute for Land Reclamation and Improvement Annual Report. Wageningen, The Netherlands. 25-37.

Yule, D. R. (1989) Irrigation management for efficient water use. In *Proceedings of the Irrigation Management Workshop*. Queensland, Department of Primary Industries, Brisbane QLD. 127-138.