A Comparison of Wheat and Canola Water Use Requirements and the Effect of Spring Irrigation on Crop Yields in the Murray Valley

by

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“Water is essential for crop production and best use of available water must be made for efficient crop production and high yields. This requires a proper understanding of the effect of water - rainfall and/or irrigation - on crop growth and yield under different growing conditions.” (Doorenbos & Kassam, 1979)
Certificate of Authorship

I  Samuel Huxley Stuart North

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Abstract

This thesis examines the potential of deficit irrigation strategies for improving farm profitability for the dominant water user group (i.e. rice growers) in the NSW Murray Valley. In particular, the study aimed to determine:

1. the relative responses of wheat and canola in the Murray Valley to a range of spring irrigation frequencies
2. local crop factors ($K_c$) and the shape of a generalised $K_c$ curve for wheat and canola
3. crop production functions for flood irrigated canola and wheat in the Murray Valley to show the profit maximising irrigation strategy when water is limited
4. the comparative ability of canola and wheat to capture deep soil moisture consistent with that remaining after rice

Experiments were conducted over two years to compare the effects of four spring irrigation treatments on wheat var. Janz and canola var. Oscar. The four irrigation strategies compared in both years were: (1) unirrigated in spring; (2) one spring irrigation; (3) deficit irrigation when the cumulative evaporation minus rainfall ($E-P$) deficit was 90 mm; and (4) full irrigation when the $E-P$ deficit was 60 mm. Agronomic measurements were made to assess the effect of the irrigation treatments on crop growth and yield and hydrologic measurements to determine crop water use.

The responses of wheat and canola to irrigation are very different; with wheat having a three-fold greater response to spring irrigation than canola. Wheat yields responded to increased water supply over a wide range up to maximum of 8.3 t ha$^{-1}$ from 920 mm. The major restrictions on wheat yield were disease and high spring temperatures. By contrast, canola had a greater initial water requirement but the yield response occurred over a fairly limited range of water supply before plateauing at around 3.4 t ha$^{-1}$ when crop water use was 470 mm.

Canola’s lack of response to levels of applied water >350 mm is attributed to: 1) its ability to resume growth and recover from an earlier period of water stress if rain falls; 2) its relatively insensitivity to drought during pod ripening and grain filling; and 3) a combination of high evaporative demand in spring, low soil hydraulic conductivity and
restricted rooting which induce water stress. It is postulated that the effect of this water stress is exacerbated by high temperatures if transpiration is reduced to the point where plants are unable to remain cool. Results are presented to indicate that canola seed yield declines by 0.7 t ha\(^{-1}\) with each 1\(^\circ\)C rise in the mean daily temperature above 13\(^\circ\)C during seed/pod development.

Yield (\(Y\)) and applied water (\(W_A\)) production functions were obtained that were considered representative of flood irrigated wheat and canola crops growing on red-brown earth and transitional red-brown earth soils in the southern Murray Darling Basin.

For wheat: \[ Y = -2.25 + 2.30\times10^{-2} \cdot W_A - 1.25\times10^{-5} \cdot W_A^2 \quad (R^2 = 0.938). \]

For canola: \[ Y = -3.40 + 2.59\times10^{-2} \cdot W_A - 2.44\times10^{-5} \cdot W_A^2 \quad (R^2 = 0.915) \]

Given that water is the limiting resource in the irrigation districts of the southern Murray Darling Basin, the profit maximising irrigation strategy for wheat is to pre-irrigate in autumn and apply 3-4 spring irrigations to attain a target yield of 6-7 t ha\(^{-1}\). For canola, the profit maximising strategy is to pre-irrigate in autumn and irrigate once in spring to attain a target yield of 3.2 t ha\(^{-1}\).

\(K_{c}\mid_{mid}\) for wheat and canola crops in the NSW Central Murray was determined to be 1.2 and 1.15 respectively. Existing crop phenology models adequately predicted the timing of key growth stages in both crops and this made it possible to determine generalised \(K_c\) curves for wheat and canola crops in the NSW central Murray Valley.

The \(K_c\) and crop stage data allowed maximum crop water requirements to be modelled for each crop over the period 1960 to 2005. The model results showed that, to avoid water stress in the spring period, canola requires one less irrigation on average than wheat in the NSW Murray Valley. For two soils with readily available water capacities (RAWC) of 55 mm and 75 mm, the modelled average number of irrigations required was 2.8 and 2.1 respectively for the canola and 3.4 and 2.6 respectively for the wheat.

The recommended irrigation strategy for wheat is to pre-irrigate and irrigate 3-4 times in spring. Applying more water to attain a higher yield is not recommended because of the diminishing marginal return. Deficit irrigation, particularly a single irrigation timed for flowering, is not recommended as it does not ensure the greatest average return per ML
and because there is a high risk of crop failure if spring rainfall is insufficient to support
a large biomass and the crop hays off.

The recommended irrigation strategy for canola is to pre-irrigate and then irrigate once
in spring to ensure 1) good moisture until 3 weeks past full flower and 2) that biomass at
flowering is maximised. Canola’s relative insensitivity to water stress during pod fill
and grain ripening means that deficit irrigation can be practiced after flowering.

When water is limiting, profits will be maximised if available supplies are spread out
over as large an area as possible to maximise the average net return per ML. Canola has
a lower water requirement, so profits will be maximised if available water supplies are
allocated to canola. However, its poor response to irrigation makes this a risky strategy.
To reduce this risk and ensure a sufficient response to spring irrigation, the following is
recommended:

1. sow early - to avoid high temperatures later in spring and to reduce the number
   of irrigations required
2. grow canola for irrigation on better soil types – hard soils restrict root growth
   and water supply to the crop. High evaporative demand and high temperatures in
   spring combine to limit yield potential on poor soils.

Canola was able to extract more water from deeper in the soil profile than wheat. The
most profitable strategy for canola is therefore likely to be to use it to de-water soil
profiles and grow it after rice. Further work is required to show whether this is
agronomically feasible and whether the results from this study are applicable to a wider
range of rice-suitable soils. It was also shown that more water was removed from the
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Chapter 1. Introduction

1.1 **Background to the issue**

Irrigation is the single largest contributor to agricultural output in Australia. It earns half of the profits from agriculture from only 0.5% of agricultural land (NLWRA 2002) and directly and indirectly contributes an estimated $12.4 billion to the Australian economy (2.3% of GDP). Approximately two thirds of Australia’s irrigated agricultural production occurs in the Murray Darling Basin (MDB) and accounts for 70% of all the water used in Australia. (Centre for International Economics 2004)

The Murray Darling Basin Commission (MDBC) recognised in 1987 that water resources in the basin had been over committed. Despite this, diversions continued to grow and an interim Cap on diversions introduced in 1995 became permanent in 1997 (MDBC 1999). Since then, 570 GL (7.4% of current water use) has been returned to the Murray River for environmental purposes and it is recommended that a further 930 GL needs to be returned to make a moderate difference to the health of the river (CRCFE 2003). In addition to these measures, Australian governments introduced market forces to the water industry in 1994 to increase economic returns from the finite resource. They did this by establishing property rights to water, creating mechanisms for trade, and charging prices for water which reflected its cost of delivery (High Level Steering Group on Water 2000).

Irrigation farmers in the MDB face increasing competition in the market for a finite and probably decreasing resource at a time when delivery charges are increasing. The result is that irrigators will need to make greater returns per ML of irrigation water if they wish to remain profitable and stay in business. It is predicted that the bulk of the impact of these changes to water policy by Australian Governments will be felt by the relatively low value annual cropping and pasture based irrigation industries of the Central Murray Valley, with water traded to higher value horticultural uses in the Riverland and Sunraysia (Heaney *et al.* 2002; Murray-Darling Basin Commission 2004).
1.2 The farming systems of the NSW Central Murray

1.2.1 Climate and soils

The climate of the NSW Central Murray is broadly typical of Mediterranean type climates. Cool conditions and low levels of solar radiation restrict plant growth during winter, and evaporation far in excess of rainfall prohibits plant growth in the summer without irrigation. The natural climate dictates that annual crops and pastures which commence growth in autumn and complete their life cycle in early summer dominate (Fitzpatrick and Nix 1970).

Five main soil groups are recognised in the NSW Murray Irrigation districts: sand hill soils, red-brown earths, transitional red-brown earths, non-self-mulching clays and self-mulching clays (Butler 1978; Hughes 1999). Two of these groups, the sodic transitional red-brown earths and the non-self mulching clays, have poor structure and poor profile and surface drainage and this restricts water entry and root growth and predisposes them to waterlogging (Grieve et al. 1986).

1.2.2 Institutional constraints

The Murray Irrigation districts of southern NSW were designed in the 1930’s as supplementary irrigation schemes, with water supplied to irrigate approximately one-third to one-tenth of each holding (NSW Department of Agriculture 1966). This low irrigation intensity has persisted and is now imposed as a 4 ML/ha limit for each irrigation farm to control the hydraulic loading on district water-tables (Beecher et al. 2002a). Only half the area of the district has been developed for irrigation and only half this developed area is irrigated in any one (full allocation) year (Evans 2004). In addition to the low irrigation intensity, the reliability of “General Security” irrigation water supplied to the district is lower than in other southern MDB irrigation areas: 70% compared to almost 100% for Murray Valley irrigators in South Australia and 96-98% for general security water in northern Victoria (Frost et al. 2003).

1.2.3 The predominant farming systems

The two main irrigation enterprises in the district are rice/pasture based mixed farming and dairying. Rice is grown on 15% of the area developed for irrigation yet consumes on
average 55-60% of the water supplied to the district. Twenty of total supply is used on pastures and 11% on winter crops, principally cereals (Murray Irrigation Limited 2003). Surface application of irrigation dominates in the district, with 50% of the developed area laid out to border check, 46% to basin systems, 2% to furrow and 2% under some form of pressure system, generally centre pivot or linear move (Evans 2004). Soil structure and drainage characteristics determine the suitability for various enterprises. Dairy pastures and border check systems predominate on the better drained, steeper and coarser textured soils. Rice farming requires basin irrigation systems and predominates on the fine textured, slowly permeable soils of the flatter flood plain.

1.3 Development of the issue

The value of irrigated production is directly related to the amount of capital invested in irrigation infrastructure (Meyer 2005) and this in turn is related to the reliability of supply and the security of tenure (Frost et al. 2003). The relatively low capital intensive (per ha), flexible (i.e. low risk) farming systems based on surface irrigated annual crops have developed in the Murray Irrigation districts in response to this. In addition, the low irrigation intensity and the reliability of winter rainfall suits the supplementary nature of irrigation in the district and the flat terrain and predominantly heavy clay (often sodic) soils suit surface irrigation application systems rather than pressure systems.

The current research and policy focus in Australia to improve water use efficiency (CRC Irrigation Futures 2004; Department of Prime Minister & Cabinet 2005) is generally interpreted as encouragement for a shift to higher value commodities like vegetables and fruit (Meyer 2005) or to more capital intensive irrigation application systems such as centre pivot/linear move systems (CRC Irrigation Futures 2004). Such a shift would require farmers in the NSW Murray Valley to increase the level of capital invested in their farms without a commensurate increase in their water supply reliability and they would have to raise this capital using their current (relatively) low value enterprise mix. Few rice farmers are willing to accept this risk, particularly as their soils are generally unsuited to horticultural production and/or pressure application systems. The dilemma they face in the NSW Central Murray is how to remain profitable when water is becoming increasingly scarce and costly, without having to raise large amounts of capital which exposes them to greater economic risk for an uncertain outcome.
1.4 **Study Objectives**

This thesis examines the potential of deficit irrigation strategies for improving farm profitability for the dominant water user group (i.e. rice growers) in the NSW central Murray Valley. The overall objective is to determine the relationship between yield and applied water (i.e. the production functions) for the major irrigated winter crops grown in the NSW central Murray (i.e. wheat and canola). Using production economic theory, this knowledge can be used to determine the profit maximising irrigation strategy when water is limited. As a result, it is hoped that irrigators will be better placed to cope with the predicted increase in water price and scarcity in the NSW Central Murray irrigation districts.

The available literature is reviewed in Chapter 2 and the following gaps are identified:

- There was little information regarding the response of canola to deficit irrigation and none regarding the relative responses of wheat and canola.
- Experimentally determined local crop factors ($K_c$) and standard growth stages lengths for estimating the maximum water requirements of canola in the Murray Valley are not available.
- No published local production functions were found for canola.
- No published studies were found which examined deep percolation losses under irrigated canola.

Given these gaps in the literature, this study aimed to determine:

1. the relative responses of wheat and canola in the Murray Valley to a range of spring irrigation frequencies
2. local crop factors and the generalised shape of the $K_c$ curve for wheat and canola.
3. crop production functions for canola and wheat in the Murray Valley and use these to ascertain the profit maximising irrigation strategy for the water limited scenario
4. the comparative ability of canola and wheat to capture deep soil moisture consistent with that remaining after a rice crop.
Chapter 2. Literature Review

2.1 Water use efficiency and water productivity

In order to gauge the effectiveness of a course of action, it is necessary to have a standard measure against which the magnitude of any resultant changes can be assessed. The focus of Australian Government policy regarding water resource management is to improve water use efficiency (WUE) so, for government, it has become important to define and measure WUE. However, the definition of WUE varies with the discipline being studied and the scale of the process being measured. This section reviews some of these definitions with the objective to determine an appropriate measure for this study.

The commonly accepted terms used by agronomists for crop WUE are transpiration efficiency ($T_e$), defined as the biomass produced per unit of water transpired, and evapotranspiration efficiency ($ET_e$) when soil evaporation is included (e.g. Taylor et al. 1983; Cooper et al. 1987; Yunusa et al. 1993). Both terms have the units of kg ha$^{-1}$ mm$^{-1}$.

Engineers use the term irrigation efficiency ($I_e$), which is defined as the ratio of water used “productively” to that supplied and is dimensionless (Doorenbos and Pruitt 1977).

A number of authors (e.g. Stanhill 1986; Oweis, et al. 1999; Barrett Purcell & Associates 1999; Meyer 2005) make the point that the word efficiency should only be used if the term satisfies the definition of an efficiency ratio (i.e. a dimensionless ratio). Because $T_e$ and $ET_e$ do not satisfy this definition, Barrett Purcell & Associates (1999) recommended using index instead of efficiency. However, $T_e$ and $ET_e$ are commonly accepted terms so their nomenclature is retained in this study.

Oweis, et al. (1999) and Meyer (2005) replaced the term WUE with water productivity ($WP$). They defined $WP$ as the ratio of saleable product (i.e. yield) expressed as a mass (kg or tonne) to the volume of water applied ($W_A$) expressed in ML:

$$ WP = \frac{Y}{W_A} = \frac{\text{Yield}}{(P + I_a + \Delta S)} $$

Equation 2-1

This is similar to Howell’s (2001) definition for a benchmark WUE (referred to here as the benchmark WP), except that Howell used effective rainfall ($P_e$) and net irrigation
depth \((I)\) instead of total rainfall \((P)\) and gross applied irrigation \((I_a)\) \((\Delta S = \text{change in soil moisture content of the root zone})\). Oweis, \textit{et al.} (1999) include monetary as well as physical terms in the ratio, so \(WP\) can have either the units \(\text{kg ML}^{-1}\) or \(\$ \text{ML}^{-1}\). (Howell 2001) reported two definitions by Bos (1980; 1985): the yield:ET ratio and the yield:water supply ratio. In this study these are called the \textit{evapotranspiration WP} \((ET_{WP})\) and the \textit{irrigation WP} \((I_{WP})\):

\[
ET_{WP} = \frac{(Y_i - Y_d)}{(ET_i - ET_d)} \quad \text{Equation 2-2}
\]

\[
I_{WP} = \frac{(Y_i - Y_d)}{I_a} \quad \text{Equation 2-3}
\]

where \((Y_i - Y_d)\) is the difference between the irrigated yield \((Y_i)\) and the rainfed or dryland yield \((Y_d)\); \((ET_i - ET_d)\) is the \textit{net} ET difference for the irrigated crop. All three of Howell’s definitions appear in recent literature (e.g. Huang \textit{et al.} 2004).

Improving \(WP\) is often seen as the most appropriate objective for farmers to follow (e.g. CRC Irrigation Futures 200); Department of Prime Minister & Cabinet 2005). However, the primary goal of the farm business is to maximise profit, not \(WP\) \textit{per se}, and these two goals are not necessarily coincident (Tanner and Sinclair 1983; Vaux and Pruitt 1983; Meyer 2005). In order to find the economic maximum, knowledge of the relationship between yield and water use (i.e. the production function) is required.

### 2.2 Crop production functions

The relationship between crop yield \((Y)\) and water use has been extensively studied and a number of comprehensive reviews have been written (Doorenbos and Kassam 1979; Barrett and Skogerboe 1980; Vaux and Pruitt 1983; Howell 1990; Oweis, \textit{et al.} 1999). If applied water \((W_A)\) is used, the relationship between \(Y\) and \(W_A\) (i.e. the crop production function) is a diminishing-return function (Figure 2-1, below). It is generally accepted to be a second degree polynomial (Stewart and Hagan 1973; Vaux and Pruitt 1983; Zhang and Oweis 1999; Zhang \textit{et al.} 2000; Huang \textit{et al.} 2004), though Martin \textit{et al.} (1984) found power and exponential functions also fitted available data.

Following earlier work by de Wit (1958) and Bierhuizen and Slatyer (1965), Tanner and
Sinclair (1983) found that, for short time scales, \( T_e \) was inversely proportional to the average vapour pressure deficit of the air during daylight hours \((e^* - e)\) such that:

\[
T_e = \frac{Y}{T} \approx \frac{k}{(e^* - e)}
\]

They demonstrated the stability of their crop-specific constant \((k)\) for crops with a leaf area index (LAI) > 3 and concluded that, whilst yields of crops varied with growing conditions, total dry matter (i.e. roots and shoots) was decreased by water deficits in proportion to the decrease in transpiration caused by the deficits. A considerable number of studies have supported this conclusion (e.g. Passioura 1976; Fischer 1979; Cooper et al. 1983; Gregory et al. 1992). Jamieson (1999) suggested the relationship was not exactly true but agreed with its approximate truth. Differences have arisen from studies on water stressed crops or when LAI < 3 but this difference is largely reconciled by reference to the dynamic nature of plant responses to water stress (Stanhill 1986).

Figure 2-1. A generalised crop production function showing the relationship between yield \((Y)\), evapotranspiration \((ET)\) and irrigation \((I_a)\) taking into account contributions from available soil water \((ASW)\) and rainfall \((P)\) during a season (after Stewart and Hagan 1973).

In Figure 2-1, the straight line between A and \((Y_{max}, ET_{max})\) is interpreted as the linear relationship between \(Y\) and \(T\) (with slope = \(T_e\)) and the positive intercept on the \(ET\) axis (A in Figure 2-1) as being equal to the soil \(E\) fraction of total crop \(ET\) (e.g. Hanks et al. 1969, Tanner and Sinclair 1983; French and Schultz 1984a). Viets (1962) and Ritchie (1983) believed the situation was more complex, with \(E\) and \(T\) (inversely) coupled so
that changing one without the other was not possible (see also Savenije 2004). Ritchie (1983) interpreted the positive intercept on the \( ET \) axis as cumulative \( E \) from planting to the time when \( \text{LAI} \approx 1 \) and after \( \text{LAI} > 1 \) the seasonal \( ET \) was both \( E \) and \( T \) (see also Fischer 1979) with the soil surface wetness determining to some extent the value of \( T \).

A substantial body of work supports the hypothesis that the \( Y - ET \) relationship is linear (Stewart and Hagan 1973; Fischer 1979; Vaux and Pruitt 1983; Morizet et al. 1984; Steiner et al. 1985; Stanhill 1986; Zhang and Oweis 1999; Huang et al. 2004) and it is apparent that \( T_e \) defines the upper limit for improving \( ET_e \) (e.g. French and Schultz 1984). However, there is debate about the constancy of \( T_e \) and the \( Y - ET \) relationship, as it exhibits considerable variability between sites, within and between species and between years/seasons (Vaux and Pruitt 1983; Hanks 1983; Morizet et al. 1984; Oweis, et al. 1999; Jamieson 1999). Attempts have been made to obtain less variable, more widely applicable \( Y\text{-}ET \) relationships using relative values (e.g. Doorenbos and Kassam 1979). Whilst these remove inter-year variability for the same crop (Hanks 1983), the relationships still varied according to species, variety, irrigation method and management, and the growth stage at which any water deficit occurs (Kirda 2000).

Stewart and Hagan (1973) explained the convex nature of the \( Y - W_A \) relationship by plotting \( Y \) against both \( ET \) and \( W_A \) on the same graph and demonstrating that the linear \([Y=f(ET)]\) and the convex \([Y=f(I)]\) functions were coincident up to a point and then diverged as \( W_A \) increased (from B to D in Figure 2-1). They attributed the divergence to non-\( ET \) losses (i.e. deep percolation, runoff and changes in soil water content) and argued that if \( I_e \) was 100\% (i.e. all irrigation used as \( ET \)) then the two functions would be identical. Differences between sites, such as different water application techniques or soil types, also affect \( I_e \), further increasing the subjectivity of the \( Y\text{-} W_A \) relationship.

Because the \( Y\text{-} W_A \) relationship is empirical, conclusions drawn from it are only valid if they are applied in circumstances similar to those from which the curve was derived and care must be exercise in extrapolating results from research plots to irrigated fields (Barrett and Skogerboe 1980; Vaux and Pruitt 1983). Their advantage is their simplicity and usefulness when general “rules” regarding the optimal use of irrigation water under given conditions are required (Yaron and Bresler 1983).
2.3 **Generalised management information from production functions**

The basic element required for the economic analysis of on-farm irrigation is the revenue function. This is shown in Figure 2-2 (below) and given by:

\[ R(W_A) = P_c f(W_A) \]  

*Equation 2-5*

where \( R(W_A) \) is revenue per ha, \( P_c \) is crop price ($/t), \( f(W_A) \) is the crop production function and \( W_A \) is the *gross* amount of water applied to the crop.

**Figure 2-2. Generalised revenue function showing points at which yield, profit, water productivity (WP) and irrigation WP (\( I_{WP} \)) are at a maximum when water supply is not limiting.**

When land is the limiting factor in production, profits are maximised when the slope of the revenue function equals the slope of the cost line (Hardaker, *et al.* 1971; English and Raja 1996). If the unit cost of water is very much less than the unit crop price, then profits increase with increasing water application until yields approach the maximum (Stewart and Hagan 1973; Heermann *et al.* 1990). This was generally the case before economic reforms were introduced (Stegman 1983; High Level Steering Group on Water 2000; Wang *et al.* 2002) and is still the case for high value agricultural products (Yaron and Bresler 1983). Maximum profit can never be coincident with maximum \( I_{WP} \) (Equation 2-3) and will only coincide with maximum yield \( (Y_{max}) \) if the price of water is zero (Vaux and Pruitt 1983; Robinson 2004). Furthermore, maximum \( I_{WP} \) can never be coincident with \( Y_{max} \) unless the increase in yield due to irrigation is zero (Figure 2-2).
Stewart and Hagan (1973) state that when irrigation water is limited and land is not, maximum profit should be sought on a per ML basis rather than per hectare. Where farming is only profitable with irrigation, they concluded that water should be concentrated and the optimal depth ($I_{opt}$) of water should be applied to a reduced area. Where farming is profitable without irrigation, they concluded that $I_{opt}$ is the lowest feasible depth in terms of practical utility while maintaining average irrigation costs per unit of water. Because the production function is convex and the unit cost for irrigation water is constant, the first profitable unit will be the most productive in terms of yield and therefore the most profitable. Stewart and Musick (1982) agreed with the potential of this strategy for increasing profits from irrigation in semi-arid regions.

![Figure 2-3. (a) Production functions for maize at four different irrigation efficiencies (1) 100\%, (2) 82\%, (3) 71\% and (4) 48\%) and (b) return functions derived from these production functions plus the cost function. Maximum net revenue occurs where the return and cost functions are separated by the greatest distance (after Barrett and Skogerboe 1980).](image)

Barrett and Skogerboe (1980) disagreed with Stewart & Hagan. They reasoned that the production function would equate to a straight line Y-ET relationship when irrigation efficiency was 100\% and, as $I_e$ decreased, would become increasingly curvilinear (Figure 2-3a). They found that when $I_e$ was high, $I_{opt}$ was close to that required to achieve maximum yield ($I_{max}$) and, as $I_e$ decreased, $I_{opt}$ as a proportion $I_{max}$ also decreased so that the optimal depth was nearly the same no matter how efficient the irrigation system (Figure 2-3b). They concluded there was a narrow range of optimal irrigation depths regardless of the $I_e$, with $I_{opt}$ for a system with low $I_e$ being much less than $I_{max}$ but little greater than $I_{opt}$ in a more efficient system. They considered it safer to
err on the side of applying more water, as the return and cost functions converged more slowly on the right hand side of $I_{opt}$ than on the left (Figure 2-3b).

Yaron and Bresler (1983) derived four agronomic-economic rules regarding the optimal on-farm allocation of available irrigation water:

1. The maximum yield physically achievable is not profitable unless water is free
2. If water availability is unrestricted at a given price, then profits are maximised when the marginal net return per unit of water is equal to this price
3. If water is scarce, then the available irrigation water should be spread out over all of the available irrigation area. Water should be allocated so that the marginal net return of water is equal across all the land units irrigated.
4. The limit to the “spreading out” process is the ability to pay for the fixed cost per unit land area. In this situation, the goal is to maximise the average net return per unit water, with some of the land left unirrigated.

Martin et al. (1989) tested the differing conclusions of Stewart and Hagan (1973) and Barrett and Skogerboe (1980) by extending Yaron & Bresler’s (1983) analysis and using a more general solution to the crop production functions (Doorenbos and Kassam 1979; Martin et al. 1984) than the earlier, experimentally derived relationships. They showed that Barrett & Skogerboe’s conclusion was nearly true when irrigated farming was considerably more profitable than dryland farming, but not when the difference in profitability of the competing irrigated and dryland enterprises was less. They concluded that there were situations when the available water should be spread over the total irrigable area and others where a smaller area should be irrigated, the actual strategy depending on the relevant costs and commodity prices.

Yaron & Bresler’s four agro-economic rules are expressed in equation form by English & Raja (1996) for a quadratic production function of the form

$$ R(W_A) = P_e f (W_A) = P_e \left( a_0 + a_1 W_A + a_2 W_A^2 \right) $$  \hspace{1cm} \text{Equation 2-6} 

and a linear cost function of the form

$$ c(W_A) = c_1 + c_2 W_A $$  \hspace{1cm} \text{Equation 2-7} 

where $c_1$ and $c_2$ represent fixed and variable costs respectively. Maximum yields are attained at $W_m$ (Figure 2-4, below) when the slope of the revenue function is zero:
\[ W_m = -\frac{a_1}{2a_2} \]  

Equation 2-8

When land is limiting, profit is maximised when the slope of the revenue and cost functions are equal and, for a crop price of \( P_c \), this occurs at \( W_l \) (Figure 2-4):

\[ W_l = \frac{c_2 - P_c a_1}{2P_c a_2} \]  

Equation 2-9

If water is limiting and extra land is irrigated with the water saved by reducing the depth of irrigation, then profit is maximised at \( W_w \) (Figure 2-4) where the slope of \( R(W_A) \) equals the average return per unit of \( W_A \) net of fixed costs \( (c_1 \text{ in Figure 2-4}) \).

\[ W_w = \left( \frac{P_c a_0 - c_1}{P_c a_2} \right)^{\frac{1}{2}} \]  

Equation 2-10

This takes into account the opportunity cost of water, a factor also considered by Stewart and Hagan (1973) and Martin et al. (1989).

---

**Figure 2-4.** Generalised cost, \( c(W_A) \), and revenue, \( R(W_A) \), functions showing the level of applied water to achieve maximum yield \( (W_m) \) and maximum profit when land is limiting \( (W_l) \) and water is limiting \( (W_w) \). The level of applied water at which the net profit is equal to that at \( W_m \) for the land limiting \( (W_{el}) \) and the water limiting \( (W_{ew}) \) case is also shown (source English & Raja 1996).
2.4 Deficit irrigation and risk

Deficit irrigation is the practice of applying less water to a crop than is required to achieve maximum yield so the crop is exposed to a level of water stress, either during a particular period or over the whole growing season. Given the previous discussion, it is clear that some level of deficit irrigation is required if the main objective of agricultural production is to maximise profits (Robinson 2004). Deficit irrigation aims to increase WP by eliminating irrigations that have little impact on yield and using the water thus saved to irrigate additional land (Kirda 2000). The potential benefits of deficit irrigation derive from three factors: increased irrigation efficiency, reduced costs of irrigation and the opportunity costs of water (English and Raja 1996).

Zhang and Oweis (1999) used English and Raja’s (1996) equations to assess a range of irrigation strategies for wheat in the Mediterranean climate of northern Syria. Irrigating to maximise net profit per ML (i.e. water limiting case) was estimated to save 40-73% of the water required for full irrigation for a yield reduction of 13%, while watering to achieve a target yield of 4-5 t ha\(^{-1}\) saved 100% in a wet year and 63% on average for a yield reduction of 31%. The water saved using this latter strategy was enough to irrigate an area over twice the size of the area irrigated under full irrigation, with a similar increase in production. Zhang et al. (2000) simulation results showed the optimum strategy for wheat in northern China was similar to Zhang & Oweis’s (1999).

Robinson (2004) simulated crop growth under various levels of water deficit using 40 years of weather data to obtain crop production functions for maize, soybean, wheat and winter (annual) pasture in the Murrumbidgee Irrigation Area of NSW. A simple non-linear programming model was used to demonstrate the efficiency gains of deficit irrigation compared to full irrigation for a representative farm. This indicated that the profit maximising strategy was to apply 25 to 64% less water per crop than with full irrigation. This was predicted to allow the irrigated area to be doubled and increase farm total gross margin by 22%. Increasing the price and/or the scarcity of water significantly increased the benefits of deficit irrigation over the full irrigation strategy.

Robinson (2004) showed that when water supply is limiting and/or the water price is high (relative to crop price), then deficit irrigation provides greater profits and higher WP than full irrigation in an area similar to the Central Murray. However, deficit
irrigation entails greater risk and this may determine whether individual farmers adopt deficit irrigation strategies (English et al. 2002). English and Raja (1996) analysed the risks associated with deficit irrigation of cotton in California, wheat in north-western USA and maize in Zimbabwe. The calculated irrigation depths (\(W_{el}\) and \(W_{ew}\) in Figure 2-4, page 12) at which profits equalled those from full irrigation (\(W_{m}\) in Figure 2-4) were used to estimate the minimum irrigation depth, below which profits were less than from full irrigation. Net income in all cases was not reduced by deficit irrigation until deficits were substantial (48 to 81% for the water limited and 30% for the water non-limited cases) and they concluded that the wide margin for error and the potential advantages made the risks associated with deficit irrigation very acceptable.

Ways of minimising the risks associated with deficit irrigation were summarised by Doorenbos and Kassam (1979). They recommended full irrigation for more water sensitive (more responsive), higher yielding or more valuable crops. For less sensitive, lower yielding or less valuable crops, they recommended deficit irrigation with available water spread over a larger area and with irrigations timed to coincide with the most sensitive growth stages.

A number of studies support these recommendations. Kirda (2000) found that only the crops and growth stages that were less sensitive to water stress generated significant water savings, with cotton, maize, wheat, sunflower, sugar beet and potato all being well suited to deficit irrigation. Pereira et al. (2002) examined alternative deficit irrigation strategies for wheat (low value) and potatoes (high value) and determined that the best option for wheat was to deficit irrigate as much land as possible with the available water, whereas the best strategy for potatoes was to apply just a light deficit and water only a fraction of the land. Timing irrigations to coincide with the most sensitive growth stages is a successful strategy for wheat, but rainfall probability and soil water availability should be taken into account (Zhang and Oweis 1999; Zhang et al. 2000).

This risks associated with deficit irrigation can also be mitigated by selecting crops or crop varieties that are drought tolerant (i.e. less sensitive) and have a short growing season (Stewart and Musick 1982) and by selecting areas with (fine textured) soils that have greater water holding capacity (Kirda 2000). Applying deficit irrigation to crops grown at times of low evaporative demand or as a supplement to rainfall also appears to increase the likelihood of success (Pereira et al. 2002; Robinson 2004).
2.5 The role of deficit irrigation in the rice based farming systems of the NSW Central Murray

Rice based farming systems use more than 75% of the water delivered to the NSW Central Murray Irrigation Districts (Rendell McGuckian 2002). For these farms, rice totally dominates summer crop production whilst cereals (principally wheat) dominate in winter, with canola practically the only non-cereal winter crop (Table 2-1).

Table 2-1. Production data from 2000-01 for the most commonly grown summer (left) and winter (right) crops in the Central Murray statistical sub-division (source; ABS 2001).

<table>
<thead>
<tr>
<th></th>
<th>Summer Crops</th>
<th>Average Yield (t/ha)</th>
<th>Winter Crops</th>
<th>Average Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (ha)</td>
<td>Production (t)</td>
<td></td>
<td>Area (ha)</td>
</tr>
<tr>
<td>rice</td>
<td>90,672</td>
<td>836,048</td>
<td>9.2</td>
<td>wheat 226,434</td>
</tr>
<tr>
<td>soybeans</td>
<td>1,844</td>
<td>3,495</td>
<td>1.9</td>
<td>barley 84,790</td>
</tr>
<tr>
<td>maize grain</td>
<td>947</td>
<td>9,164</td>
<td>9.7</td>
<td>canola 44,405</td>
</tr>
<tr>
<td>millet</td>
<td>522</td>
<td>809</td>
<td>1.5</td>
<td>triticale 10,481</td>
</tr>
<tr>
<td>sorghum</td>
<td>259</td>
<td>875</td>
<td>3.4</td>
<td>oats 8,212</td>
</tr>
<tr>
<td>field peas</td>
<td>5,781</td>
<td>4,421</td>
<td>0.8</td>
<td>faba beans 734</td>
</tr>
<tr>
<td>lupins</td>
<td>1,804</td>
<td>2,674</td>
<td>1.5</td>
<td>chick peas 381</td>
</tr>
</tbody>
</table>

Rice is the dominant summer crop because none of the alternatives are as profitable, have such low labour requirements per ML, or are as low risk in production and marketing (Beecher et al. 1995; Rendell McGuckian 1998). Rice is better suited to the heavy clay (often sodic) soils of the region than maize, is more profitable than soybeans and millet, and is not constrained by temperature to the same extent as sorghum (Spenceley, et al. 2003) and cotton (Dowling 2001). However, the management options available to irrigators in the Central Murray for improving the WP of rice are limited.

Rice water use is relatively fixed (14-16 ML ha\(^{-1}\)). The crop requires ponded conditions for 120-170 days (Oct - Mar) to avoid cold temperature damage and moisture stress so its water use is primarily determined by soil type, layouts, growing season length and evaporative demand (Beecher et al. 2002). Intermittent irrigation until two weeks before panicle initiation can reduce water use by 18-25% without yield loss (Heenan & Thompson 1984; Heenan & Thompson 1985). However, this strategy has not been adopted because the labour requirement is higher and, until recently, weeds could not be
managed (Humphreys et al. 2003b). Furthermore, deep drainage and surface runoff losses have been reduced to a practical minimum through improved rice soil suitability criteria and drainage recycling (Murray Irrigation Limited 2003).

Rice WP roughly doubled between 1980 and 2000, mainly through an increase in yields (Humphreys et al. 2003b). However, average and best practice yields are now 70% and 100% respectively of what was considered the physiological potential (Beecher et al. 1995). Consequently, significant improvement in rice WP through further large yield increases may not be within the capacity of individual irrigators.

Furthermore, there are a range of management strategies for improving WP that are not easily applied to rice. These include increasing soil cover (mulch); growing crops in winter to take advantage of rainfall and higher $T_e$; using residual moisture from preceding irrigated crops; improving irrigation scheduling; and reducing the frequency of irrigations (Stewart & Musick 1982; Cooper et al. 1987; Hatfield et al. 2001; Howell 2001; Sinclair & Muchow 2001; Wang et al. 2002; Debaeke & Aboudrare 2004).

All these factors indicate that there is greater potential to improve the WP of rice farms in the Central Murray Valley by focussing on the non-rice phase of the crop rotation (i.e. winter crops). This conclusion is supported by Stewart and Musick’s (1982) discussion and the results presented by Robinson (2004).

### 2.5.1 The role of wheat

Wheat is the most commonly grown crop in the world (Pingali 1999) and there is a large body of research into its water use requirements (e.g. Fischer 1979; Angus et al. 1980; Cooper et al. 1983; Cooper et al. 1987; Zhang and Oweis 1999; Oweis, et al. 1999). This makes it a good standard with which to compare alternative winter crops. It is also the crop most commonly grown in rotation with rice (Table 2-1), being more tolerant of waterlogging than both barley and oats (Grieve et al. 1986). This is an advantage where crops are sown after rice to reduce groundwater accessions (Humphreys et al. 2001).

District average wheat yields from irrigation farms in the NSW Central Murray are 3.3 t ha$^{-1}$ compared to 1.5 t ha$^{-1}$ from dryland farms (ABARE 1998). Yields of up to 6.2 t ha$^{-1}$ have been reported from “best growers” (average 5.2 t ha$^{-1}$; Beecher et al. 1995) and yields of 7.0 to 8.9 t ha$^{-1}$ have been reported from irrigation experiments on “good” soils
in southern NSW (Cooper 1980a; Thompson and Chase 1992; Stapper and Fischer 1990a). The difference between the average and maximum yields suggests there is potential to increase irrigated wheat yields provided favourable soil conditions.

2.5.2 The role of canola

Canola is the most significant of all the broadleaf winter crops grown in the NSW Central Murray (Table 2-1). Lentils, chickpeas, lupins and field peas are intolerant of waterlogging (Carter & Materne 1997; Landers, et al. 2000; Manning, et al. 2000; Simmons 1989) so are not suited to the heavy soils and flat terrain of rice systems. Faba beans are well suited to the climate and soils of the district and do respond well to irrigation on heavy clay soils (Matthews and Marcelllos 2003), but their susceptibility to foliar disease and higher input costs are a barrier to their adoption.

Canola in crop rotations is said to reduce root diseases, improve soil structure and prevent the build up of herbicide resistant weeds (Scott et al. 1999). It has been shown to improve yields of the following wheat crop, with wheat after canola out yielding wheat after wheat by 19% on average (Angus 2002). This “break crop” effect has been well documented (Angus et al. 1991; Asseng et al. 1998; Kirkegaard et al. 1997; Norton et al. 2003) and shown to have a positive effect on gross margins (Walton 1998; Angus et al. 1999). It is mainly due to the control of cereal root diseases by biofumigation and the absence of a grassy host (Angus & van Herwaarden 2001; Angus 2002). In the rice farming systems of southern NSW, this function is fulfilled by the rice crop. However, with more limited water supplies and a reduced area of rice there will be a greater need for crops such as canola in the rotation to provide these benefits.

Scott et al. (1999) found canola has a place in crop rotations in southern NSW if it can return at least $570/ha, so yields need to be at least 1.7 t ha$^{-1}$ for canola to be profitable given the the long term median price of $350/t (Australian Bureau of Agricultural Economics 2005). The district average from irrigation farms in the NSW Central Murray is 1.8 t ha$^{-1}$ (ABARE 1998) and growers are turning away from canola. Nevertheless, there is potential to increase canola yields using irrigation, with “best growers” achieving yields of between 1.8 and 3.6 t ha$^{-1}$ (average 2.6 t ha$^{-1}$; Beecher et al. 1995) and reports of 3.8 to 5.2 t ha$^{-1}$ from irrigation experiments in non-rice systems in the Victorian Murray Valley (Wright et al. 1988; Taylor et al. 1991; Taylor & Smith 1992).
2.6 **Crop development models for the Murray Valley**

Models relating crop development rate to the prevailing climate can be used to predict when crops will be at a drought-sensitive stage. Growing degree-days (GDD) or day-degrees (°Cd) are used as a measurement scale for crop development:

$$GDD = \sum_{S_1}^{S_2} (T_m - b_o)$$  \hspace{1cm} \text{Equation 2-11}

where \(T_m\) is mean daily temperature, \(b_o\) is the base temperature and \(S_1\) and \(S_2\) are two development stages.

### 2.6.1 Wheat

Development rate in wheat essentially depends on genotype, temperature and day-length, but environmental stresses, particularly heat, may shorten growth phases. Temperatures of 0°C or 4°C are commonly used as the base temperature for physiological processes in wheat, whilst the optimum temperature for growth is 20-25°C. Spring wheats have a very mild to no response to vernalisation and most cultivated wheats are quantitative long-day plants. (Acevedo *et al.* 2002)

In their review of wheat phasic development, Slafer and Rawson (1994) confirmed that all wheat cultivars were sensitive to temperature, developing faster and heading earlier as temperature increased. They reported doubt about the actual values of base and optimal temperatures for different cultivars and about the linearity of the response to thermal time and considered that all genotypes differed in their response to temperature. This led them to conclude that it would be unwise to use the responses to temperature of one genotype to predict the responses of another and that the complexity of responses made modelling and forecasting across different environments exceedingly difficult.

Jamieson *et al.* (1998) disagreed with Slafer & Rawson’s conclusions, believing that the apparent complexity was a product of the phenological framework that they used for their analysis. They derived a simpler model based on temperature at the apex and the rate of production and number of leaves on the main stem. They found an assumption of a common base temperature of 0°C fitted published data, that only mean daily temperature was required to calculate leaf appearance rates and that leaf appearance rate
declined at mean temperatures >22°C. McMaster et al. (2003) also observed a linear rate of appearance of leaves with GDD (mean air temperature, base 0°C) and a range of 80 to 120°Cd per leaf is reported, the actual rate being determined by the environment (Klepper 1990). A rate of 110°Cd per leaf has been suggested for Australia (Cole 2001).

In a comprehensive study of phasic development in 25 bread wheats (Triticum aestivum) at Griffith, NSW, Stapper and Fischer (1990a) found that the rate of leaf appearance per °Cd increased with delayed sowing, decreased at high plant density and differed between genotypes. They recommended leaf appearance related development stages should not be used as a basis to predict spike-based development stages. Instead, they classified each cultivar according to six maturity types and related GDD between sowing and mid-flowering (DC65) to sowing date (Julian date) for each group for mid-March to mid-September sowings (13 dates in 4 years) using non-linear regression. They obtained $R^2$ values > 0.90 for four of the six maturity types ($R^2 > 0.8$ for all types) using a base temperature of 3°C. The length of the average post-flowering period (DC65-DC86) was 602°Cd (base temperature 3°C) and the average grain filling period (DC70.7-DC86) was 340°Cd (base temperature 8°C), with no significant difference between genotypes.

### 2.6.2 Canola

Hodgson (1978) reported on the variation in response of Brassica oilseeds to temperature, photoperiod and vernalisation and developed a model of crop phenology for northern NSW. More recently, Robertson et al. (2002) quantified the phenological response of canola and Indian mustard to temperature, vernalisation and photoperiod and developed a model for canola in Australia that quantified the photo-thermal response for time to flowering. They confirmed that Brassica species are long-day plants and determined the existence of a photo-period insensitive phase for B. napus.

Reported base temperatures for canola range from 0°C to 7°C (Hodgson 1978; Morrison, et al. 1989), with a base temperature of 5°C commonly accepted (Mendham and Salisbury 1995; Canola Council of Canada 2001). Vigil et al. (1997), however, recommended a base temperature of 0°C. This was used by Gabrielle et al. (1998) in the French canola model CERES and was confirmed as the base temperature for canola development under Australian conditions by Robertson et al. (2002).
In their phenology model, Robertson et al. (2002) describe crop development to flowering in terms of 4 stages, with daily thermal time accumulated during each stage until thresholds are satisfied and then development progresses to the next stage. The duration of the first and fourth phases are mainly controlled by temperature (Mendham and Salisbury 1995), the second (juvenile) phase by vernalisation and the third (vegetative) phase by photoperiod. The start and finish of these phases correspond to stages 0.0, 1.0, 2.01, 3.3 and 4.5 of Sylvester-Bradley & Makepeace (1984).

The period from 50% flowering to physiological maturity was not examined by Robertson et al. (2002) but is also determined solely by temperature (Mendham and Salisbury 1995; Robertson et al. 1999). A length of 715°Cd (base temperature of 4.2°C) was predicted for all genotypes by Mendham et al. (1981).

Fertiliser (N) application does not affect the rate of phenological development in canola (Hocking et al. 1997b).

### 2.7 Calculating irrigation water requirements

Guidelines for computing maximum crop water requirements are provided by Allen, et al. (1998). In this approach, the effect of crop type on water use is incorporated in a crop factor term ($K_c$) and the effect of climate is incorporated in a reference crop evapotranspiration term ($ET_o$). $ET_o$ is either calculated from weather data using one of many different equations, or estimated from class A pan evaporation ($E_{pan}$) and $K_c$ is calculated as the ratio of actual $ET$ to $ET_o$ (Burman & Pochop 1994; Allen, et al. 1998).

Actual crop evapotranspiration ($ET_c$) is then calculated according to:

$$ET_c = ET_o \times K_c = (E_{pan} \times K_p) \times K_c$$

Equation 2-12

The empiricisms in the different relationships used to estimate net radiation and calculate the wind function in $ET_o$ equations can produce a 23% difference in estimates of $ET_o$ (Batchelor 1984). Bethune, et al. (2001) and Kingston, et al. (2001) found the Penman-Monteith $ET_o$ provided reliable estimates of the maximum water requirement of rice and pasture in the Murray Valley. There is a strong linear correlation (not 1:1) between Penman-Monteith $ET_o$ and $E_{pan}$ which makes $E_{pan}$ as good a measure of crop water requirement but it has the advantage of being able to do it at one tenth of the cost.
(Tyagi, *et al.* 2000; Stanhill 2002). Where pans are used, however, estimates of $ET_o$ should be based on observations over periods of 10 days or longer (Allen, *et al.* 1998).

Data from lysimeter studies at Griffith were used to develop a locally calibrated Penman combination equation ("Penman-Myer") (Meyer 1999; Meyer, *et al.* 1999). Comparisons showed there was a strong correlation between Penman-Meyer $ET_o$ and both $E_{pan}$ and Penman-Monteith $ET_o$, but $E_{pan}$ was about 7-8% higher (up to 30% higher when evaporation >10 mm/day) and Penman-Monteith $ET_o$ was consistently about 30% lower (Meyer, *et al.* 1999). At Tatura, Bethune *et al.* (2001) found that Penman-Monteith $ET_o$ values were lower than Penman-Meyer predicted $ET_o$, but by 24%.

At a national workshop in June 2002, it was proposed to adopt the Penman-Monteith equation as a standard for Australia (NPIRD 2002). The 24-30% difference between Penman-Monteith and Penman-Meyer estimates of $ET_o$ is a potential source of confusion, particularly given that $K_c$ values for wheat, soybeans, maize, lucerne, rice and pasture obtained using the Penman-Meyer equation at Griffith (Meyer, *et al.* 1999) have been widely adopted in the irrigation areas of the southern Murray-Darling Basin.

### 2.7.1 Growth stage length

Allen, *et al.* (1998) defined four crop growth stages: an initial stage from sowing to 10% ground cover; a crop development stage from 10% ground cover to effective full cover (i.e. LAI ≥ 3); a mid-season stage from effective full cover to the start of maturity; and a late season stage from the start of maturity to harvest or full senescence

**Wheat**

Allen, *et al.* (1998) provide crop growth stage lengths for wheat for a range of example locations and climates. Values for wheat sown in March/April between 35-45° Latitude differ markedly from those estimated by Meyer, *et al.* (1999) for spring wheat sown on the 15th May at Griffith and grown under average temperatures (Table 2-2).

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>Development</th>
<th>Mid-season</th>
<th>Late Season</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>35-45° Latitude (Allen)</td>
<td>20</td>
<td>25</td>
<td>60</td>
<td>30</td>
<td>135</td>
</tr>
<tr>
<td>Griffith, NSW (Meyer)</td>
<td>5</td>
<td>65</td>
<td>85</td>
<td>35</td>
<td>190</td>
</tr>
</tbody>
</table>
In the initial stage, LAI < 1 (Tyagi et al. 2000) and $E$ and the duration of soil surface wetness almost totally dominate $ET$ (Ritchie 1983). At Griffith, Meyer, et al. (1999) showed that the initial stage finished at emergence and $K_c$ then increased linearly to the time when LAI > 3. The data presented by Keefer (1977), Cooper (1987), Meyer et al. (1987) and Tyagi et al. (2000) all fit this model, with maximum $K_c$ occurring between booting and heading when LAI > 3.

Meyer, et al.’s (1999) results agree with Hedditch’s (1985) statement that the time from DC65 to DC86 is commonly accepted to be 35 days for wheat in the Murrumbidgee valley. However, this is at odds with Stapper and Fischer’s (1990a) finding that the length of the average post-flowering period is 602°Cd (>3°C), which equates to approximately 45 days in the Murray Valley for a mid-November maturity.

Canola
Canola is not included in the list of crops for which Allen, et al. (1998) provides growth stage lengths and no (local) growth stage lengths were found in the literature. In the irrigation areas of southern NSW it is presumed that canola is similar to wheat: i.e. 190 day total growing season length for a 5th May sowing and a linear increase in $K_c$ from emergence to LAI >3 (Edraki, M. 2001, pers. comm.). Whilst canola and wheat have similar total growing season lengths (Harbinson et al. 1986), the latter assumption may be in error as canola seedlings do not grow as quickly initially as cereals (Weiss 1983).

2.7.2 Crop factors ($K_c$)

Wheat
$K_c$ values for irrigated wheat from a number of sources are shown in Table 2-3. The difference between the $K_c$ values for use with the Penman-Monteith and Penman-Meyer equations is evident, though the difference does not appear to be as large as the 24-30% found in summer for rice by Meyer, et al. (1999) and Bethune et al. (2001). A number of advisory publications give $K_c$ values for wheat growing in the Murray Valley for each month of the growing season (Smith and Gibbs 1997; Hughes 1999; Giblin and Lacy 2003). All of them recommend that their $K_c$ values be used with Penman- Meyer $ET_o$ from the CSIRO weather station network in southern NSW for calculating $ET_c$. 

22
Table 2-3. Published crop coefficients for irrigated spring wheat for use with either the Penman-Monteith (Allen, et al. 1998) or the Penman-Meyer (Meyer 1999) ET<sub>o</sub> equations.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>Crop Growth Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial</td>
</tr>
<tr>
<td><strong>K&lt;sub&gt;c&lt;/sub&gt; for use with Penman-Monteith ET&lt;sub&gt;o&lt;/sub&gt;</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keefer (1977)</td>
<td>Emerald, Qld</td>
<td>0.25</td>
</tr>
<tr>
<td>Cooper (1987)</td>
<td>Trangie, NSW</td>
<td>0.3</td>
</tr>
<tr>
<td>Allen, et al. (1998)</td>
<td>universal</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>K&lt;sub&gt;c&lt;/sub&gt; for use with Penman-Meyer ET&lt;sub&gt;o&lt;/sub&gt;</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meyer, et al. (1999)</td>
<td>Griffith, NSW</td>
<td>0.3</td>
</tr>
<tr>
<td>Smith &amp; Gibbs (1997); Hughes (1999)</td>
<td>Murray Valley</td>
<td>0.3</td>
</tr>
</tbody>
</table>

1. Keefer’s (1977) crop coefficients were converted from values for use with <i>E<sub>pan</sub></i> data using a K<sub>p</sub> of 0.8.

Canola

K<sub>c</sub> values for canola for use with Penman-Monteith ET<sub>o</sub> are given as 0.35 for the initial stage, 1.0 to 1.15<sup>1</sup> for the mid-season stage and 0.35 for the end of season stage for crops with a maximum height of 0.6 m (Allen, et al. 1998). Hodgson (1978) assumed a whole of season K<sub>c</sub> for rapeseed of 0.75 for use with <i>E<sub>pan</sub></i> data in northern NSW. This equates to a K<sub>c</sub> of 0.94 for use with Penman-Monteith ET<sub>o</sub>, provided K<sub>p</sub> is 0.8. Smith & Gibbs (1997) and Hughes (1999) give K<sub>c</sub> values for canola and Penman-Meyer ET<sub>o</sub> in the Murray Valley (Table 2-4) but don’t describe how these values were obtained. The K<sub>c</sub> values for canola used in CSIRO’s SIRAG-PC program are lower (Table 2-4), but it is acknowledged that these are “educated guesses” (Edraki, M. 2001, pers. comm.).

Table 2-4. Crop factors for canola in the Murray Valley (Hughes 1999; Giblin & Lacy 2003; Smith & Gibbs 1997) and at Griffith (Edraki, M. 2001, pers. comm.) for use with Penman-Meyer ET<sub>o</sub>.

<table>
<thead>
<tr>
<th></th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murray Valley</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Griffith</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>0.7</td>
<td>0.75</td>
<td>0.75</td>
<td>0.7</td>
<td>0.4</td>
</tr>
</tbody>
</table>

A literature search of Land & Water Australia’s Streamline database using the key words canola or rapeseed or Brassica and crop factor or crop coefficient failed to find any publications. It appears from the literature searched that no experimentally derived crop factors have been obtained for canola in the southern MDB.

<sup>1</sup> the lower value is for rainfed crops having less dense plant populations
2.8 **Irrigation management**

2.8.1 **Autumn pre-irrigation**

In the Murray Valley, pre-irrigation of winter crops in autumn is recommended for paddocks with less than 50% plant available soil water as a low risk strategy given the climate, soils and irrigation layouts of the district (Lolicato 2002; Giblin & Lacy 2003). Pre-irrigation is recommended for late February, but irrigation finishing at the start of April has been shown to have a definite moisture benefit for winter crops in 86% of years (Fisher 2002). However, this needs to be weighed against the risk of waterlogging in a wet winter (Giblin & Lacy 2003).

There has been a shift in practice by rice-growers away from fallowing paddocks over-winter, to burning rice stubbles shortly after harvest and direct drilling wheat into the residual moisture. This is done to take advantage of the water left in the profile after rice and has been shown to reduce groundwater accessions and improve WP in rice farming systems (Humphreys & Bhuiyan 2001; Humphreys et al. 2001).

2.8.2 **Spring irrigation of wheat**

The management of irrigated wheat is well described in reviews such as those by Robins et al. (1967), Doorenbos & Kassam (1979), Musick & Porter (1990) and Curtis, et al. (2002). In the southern MDB, wheat irrigation requirements have been comprehensively studied and its management is now well understood. Studies into the effects of different fertiliser (N) rates and irrigation frequencies on yields (Cooper 1980a; 1980b), the timing of water deficits (Thompson & Chase 1992), phenology (Stapper & Fischer 1990a; 1990b; 1990c) and water use (Meyer et al. 1987; Steiner et al. 1985; Meyer, et al. 1999) have all been incorporated into advisory publications which outline best management practices for irrigated wheat (e.g. Giblin and Lacy 2003).

The recommended strategy for wheat in the southern MDB is (Giblin & Lacy 2003):

- In paddocks with reasonable subsoil moisture contents, one spring irrigation at head emergence for crops with the potential to yield less than 5.0 t ha\(^{-1}\).
- Two spring irrigations timed for head emergence and the start of flowering for crops with the potential to yield 5.0 to 6.0 t ha\(^{-1}\).
• Full irrigation of crops with >6.0 t ha\(^{-1}\) yield potential, entailing 3-4 irrigations on heavy clay soils and 4-5 irrigations on red loams, scheduled according to crop demand up to the late milk stage.

• Water early in spring to reduce the risk of scalding.

Full irrigation with 3-5 spring irrigations to achieve > 6.0 t ha\(^{-1}\) is considered a risky strategy in the Murray Valley. This is because of the difficulty in achieving these high yields on slow draining soils and irrigation layouts and the (perceived) high probability that the net returns from the final irrigations will be lower than the net returns from the alternative use for that water (i.e. irrigation of rice). One spring irrigation at head emergence has been shown to increase yields by about 0.9 t ha\(^{-1}\), so the preferred strategy is to target yields of 5.0 t ha\(^{-1}\) (Lacy and Thomas 2001).

### 2.8.3 Spring irrigation of canola

The \(K_c\) values for canola in Table 2-4 (page 23) show there is a marked difference in opinion as to canola’s maximum water requirement in the southern MDB. One set of \(K_c\) values (Smith & Gibbs 1997; Allen, et al. 1998; Hughes 1999) indicate that canola’s maximum water requirement is similar to wheat, whereas the CSIRO Griffith values indicate a maximum water use that is \(\frac{3}{4}\) that of wheat. Current advice is also conflicting: Colton and Sykes (1992) state that canola water requirements are different to wheat, whereas Queensland Department of Primary Industries and Fisheries (2005) state that canola has a similar water requirement to wheat.

Post flowering irrigations which fully satisfy crop water demand have been shown to significantly increase canola yields in Australia. In Tasmania, 100 mm of water applied in two post flowering irrigations increased yields of autumn sown rapeseed from 3.5 to 5.2 t ha\(^{-1}\) (Mendham \textit{et al.} 1984) whilst 1 and 3 irrigations of 50 mm increased yields from 275 to 287 and 420 g m\(^{-2}\) respectively (Rao & Mendham 1991a). At Tatura in Victoria, 3 spring irrigations increased yields from 2.3 to 3.7 t ha\(^{-1}\), leading Wright \textit{et al.} (1988) to conclude that irrigation of rapeseed was worthwhile, especially after flowering and in combination with high rates of N. In Western Australia, fully irrigated \textit{B. napus} crops achieved 3.30 t ha\(^{-1}\) compared to 2.13 t ha\(^{-1}\) from crops in which drought was imposed at pod-filling (Richards and Thurling 1978a). In all these examples, crops were
not water stressed until after flowering and pods per m² was the main yield component which contributed to the response to irrigation.

Whilst there appears to be a yield advantage from watering to avoid moisture stress after flowering, Richards and Thurling (1978a) found that the yield advantage from fully irrigating was even greater when drought was imposed earlier. They achieved mean seed yields of 3.30 g plant⁻¹ from fully irrigated plants compared to 1.51 and 1.43 g plant⁻¹ from plants subjected to drought from stem elongation and flowering respectively. Bernadi (1996) confirmed the importance of avoiding moisture stress during flowering, finding that it reduced both dry matter and seed yield, with the effects increasing as potential yield increased. He recommended the first spring irrigation occur before predawn plant water potential fell below -0.4 MPa. Lower potentials accelerated the rate of leaf loss during flowering, reducing N mobilisation from senesced leaves and lowering yields. He advocated full irrigation at Condobolin, NSW, with a second irrigation at the end of flowering and, if weather conditions were hot, a further irrigation 2-3 weeks later.

Colton and Sykes (1992) advise that irrigation should start in August unless the soil profile has been wet to 60-80 cm by winter rainfall, with the first irrigation timed to avoid any reduction in growth due to water stress. McCaffery (2004) stated that canola required irrigating in spring earlier than wheat and recommended the first irrigation be timed when plant available water (PAW) was at 60% (compared to 50% for wheat: Meyer & Green 1980). McCaffery (2004) also noted that the best crops in southern NSW irrigation districts received 2 to 4 spring irrigations in addition to an autumn pre-irrigation and, in 1994 (a drought year), received an autumn and 3 to 4 spring irrigations (4 to 5.5 ML ha⁻¹). In more normal seasons, growers were expected to irrigate 2 to 3 times in spring, which was one less irrigation than for mid-maturing wheat.

In the Murray Valley, Lacy and Thomas (2001) found the majority of canola crops are watered at 50% flowering, which is too late for irrigation to have much effect on yield. These late irrigations increased paddock yields on average by only 0.2 t ha⁻¹, compared to 0.6 t ha⁻¹ in crops that were watered at the start of flowering. For similarly reasons as applied to wheat, Full irrigation (3-5 spring irrigations to achieve 3.5 t ha⁻¹) is seen as a risky strategy in the Murray Valley, so the current recommendation is to target yields of 2.5 t ha⁻¹ and apply only one early (i.e. pre-flowering) spring irrigation.
2.9 Critical growth stages

2.9.1 Wheat

Wheat yields are particularly sensitive to water deficit at two main stages. The first occurs at terminal spikelet initiation when plants are starting a very rapid phase of growth and tiller number and spikelet size is being determined. Any stress during this period reduces yields by forcing the plant to abort tillers or by leaving the lower florets on the heads undeveloped. This occurs when the spike is about 1 cm above the crown of the plant (DC 31). The second (most) sensitive stage occurs at head emergence (DC53), which coincides with meiosis and pollen and embryo formation. Any stress at this time reduces yields by reducing the number of grains per spikelet. (Acevedo et al. 2002)

Though not as sensitive as earlier stages, stress beginning at early grain filling affects yields by reducing grain size and “pinched” grain may lead to loss of grain quality (Doorenbos and Kassam 1979). In the Murrumbidgee Irrigation Area, moisture stress (i.e. PAW < 50%) during spike emergence and flowering reduced yield from 7.0 to 3.3 t ha\(^{-1}\) through reductions in spikes m\(^{-2}\) (37%), individual grain weight (15%) and grain number per spike (13%), whereas stress during grain filling only reduced yield by 20%, mainly through a 16% reduction in individual grain weight (Thompson & Chase 1992).

Zhang & Oweis (1999) found the most sensitive stage to water stress was from stem-elongation to booting. However, after examining the rainfall probability and soil water availability during the growing season in the Mediterranean climate of northern Syria, they found there was a low probability of drought occurring during this stage. They concluded that the best use of irrigation was likely to be achieved by applying it in the period from booting to grain-filling.

2.9.2 Canola

Opinions as to the most drought sensitive stage in canola differ. Bramm (1981) showed that the critical growth stage of rapeseed, with its highest water requirement, was the period between flowering and ‘green maturity’. Richards & Thurling (1978a) found B. napus yields were markedly reduced when drought occurred at any time during reproductive development (i.e. from stem elongation or floral initiation) but cultivars
were most sensitive when drought commenced at flowering and least sensitive when drought started at the beginning of pod filling. For Australian conditions, Walton et al. (2003) recommended spring irrigation be applied to remove water stress in the flowering period, as soil moisture deficits after flowering reduced yields by 50% due to seed abortion and a reduction in the number of pods per plant. Jensen et al. (1996) found that seed yield was less affected by drought imposed during the vegetative and flowering phase than from the end of flowering.

The most critical phase occurs when pod walls are growing rapidly during the three weeks following full flower and seeds are likely to abort if plants were water stressed during this time (Mendham et al. 1981). Mendham et al.’s (1984) finding that the retention of many seeds per pod was the key factor to achieving high yields supports this. Mailer & Cornish (1987) also found that the period after flowering was the most sensitive period, during which water stress decreased yield, oil content and 1000-grain weight. However, in experiments in northern Victoria, the main yield component which contributed to the yield response to nitrogen and irrigation (Wright et al. 1988; Taylor et al. 1991) and sowing date (Taylor & Smith 1992) was the number of pods per m$^2$.

High yield in canola is determined by (1) the ability of the crop to support the sequential determination of number of pods, number of seeds and then seed growth, and (2) the effects of environmental conditions while these components are being determined (Mendham et al. 1984).

2.10 Production functions and deficit irrigation

2.10.1 Wheat

Wheat’s drought tolerance reduces its critical stage sensitivity for yield compared with many other crops and permits irrigation management involving a wide range of deficits (Musick & Porter 1990). Deficit irrigation, rather than supplemental irrigation to satisfy full irrigation requirements, can thus be recommended in semi-arid regions where rainfall is a significant contributor to crop water requirements (Stewart and Musick 1982; Oweis & Ryan 1998; Oweis, et al. 1999, Oweis et al. 2000; Wang et al. 2001). However, this strategy requires an understanding of the relationship between $Y$ and $W_A$ and both linear and curvilinear responses have been reported (Musick & Porter 1990).
French & Schultz (1984a; 1984b) assumed that wheat crops in South Australia had similar $E$ (110 mm) and concluded that the highest yields at a given $ET$ had a relatively uniform maximum $T_e$ for biomass (55 kg/ha/mm) and grain (20 kg/ha/mm). They found the relationship between actual yield and rainfall was curvilinear and attributed the increasing difference between actual and potential yields with increasing rainfall to sub-optimal management and environmental conditions (e.g. less than optimal fertility, pests and disease, delayed sowing, low temperatures, weeds, water stress and waterlogging).

Cooper (1980b) measured the volume of irrigation water applied to small plots and derived a curvilinear $Y-W_A$ production function for semi-dwarf wheat at Leeton, NSW (Figure 2-5). From this he concluded that the optimum irrigation frequency lay between 3 and 7 irrigations. The curvilinear response was attributed to the small plot size (15.2 m by 2.7 m) and large inter-plot space (2 m) which was believed to have increased $ET$ in the wet plots and evaporation from the border areas because of increased advective energy. Deep percolation and lateral flow were not measured but were assumed very low or non-existent. This assumption was likely to have been incorrect.

By contrast, Steiner et al. (1985) derived a linear production function for wheat at Griffith. Based on this, they concluded that irrigation must aim to maximise $ET$ by avoiding water stress at all stages of growth (i.e. full irrigation). However, theirs was a $Y-ET$ relationship rather than a $Y-W_A$ relationship as it did not include non-$ET$ losses. In particular, the depth of applied water was determined from pre- and post-irrigation soil water measurements, so evaporative and deep percolation losses at each irrigation event were not accounted for. Although not noted, French & Schulz’s relationship delineates the upper limit for yield in this and the other experiments quoted by the authors, including those of Cooper (1980b) and Thompson & Chase (1992).

Zhang & Oweis (1999) obtained a relationship between $Y$ and $ET$ for bread wheat at Tel Hadya in Syria that was very similar to Steiner’s (slope = 0.16 kg ha$^{-1}$ mm$^{-1}$). However, the relationship between yield and rainfall plus irrigation (i.e. $Y-W_A$) was curvilinear. Based on this, the authors recommended irrigating to achieve a target yield of 4-5 t/ha or to maximise net profit per ML, rather than irrigating to maximise yield or net profit per ha. Curvilinear $Y-W_A$ production functions have also been derived for wheat in the North China Plain region (Figure 2-5), enabling recommendations to be made to reduce
the number of irrigations from four to one, two or three irrigations of 60 mm in wet, normal and dry years respectively (Zhang et al. 2000; Wang et al. 2001).

Figure 2-5 shows that Zhang & Oweis’ (1999) production function is quite similar to Cooper’s (1980b). The fact that both curves were obtained in Mediterranean type climates suggests the doubts about the validity of Cooper’s $Y-W_A$ function may be unfounded. If so, its use for determining optimum irrigation strategies for wheat in the southern MDB may be justified. However, differences between sites (i.e. high productivity at Luancheng and low productivity at Hengshui) and between experiments on the North China Plain (Zhang et al. 2000: Wang et al. 2001) illustrates the need to derive production functions for local crops and conditions.

![Figure 2-5. Wheat grain yield as a function of total applied water from published studies.](image)

2.10.2 Canola

Hocking et al. (1997a) derived a potential $T_e$ of 12.5 kg ha$^{-1}$ mm$^{-1}$ for oilseeds (canola, Indian mustard and Linola) and Walton et al. (2003) note that the $T_e$ for potential seed yield is 10-12 kg ha$^{-1}$ mm$^{-1}$. Nielsen (1997), working on dryland crops in Colorado, fitted a linear regression to canola seed yield and water use data and showed that, on average, canola $T_e$ was approximately 7.7 kg ha$^{-1}$ mm$^{-1}$ after the first 150 mm of water use. However, fitting a line with a slope of 12.5 kg ha$^{-1}$ mm$^{-1}$ to Nielsen’s (1997) data encompasses all of his data points in a similar manner to that used by French & Schultz (1984a) for wheat in South Australia.
Unlike wheat, no studies specifically dealing with deficit irrigation of canola were found in the literature. However, a number of studies are reported in which various levels of irrigation were applied (Figure 2-6). In the first of these, in Spain, only a relatively small response to irrigation was observed: 0.1 t ha\(^{-1}\) between one and two irrigations and 0.5 t ha\(^{-1}\) between one and three irrigations (Munoz and Fernandez 1978). Clarke & Simpson (1978) achieved a greater response by scheduling irrigations according to tensiometer readings (-50 kPa at either 20 or 40 cm) and observed differences of 0.7 t ha\(^{-1}\) between zero and 2 irrigations and 0.9 t ha\(^{-1}\) between 2 and 5 irrigations. Their dryland yields were considerably lower than Munoz & Fernandez’s, so there was greater potential for them to increase yields to around the 3 t ha\(^{-1}\) level achieved by Munoz & Fernandez.

In India, the limit for high yields may be lower, at roughly 2 t ha\(^{-1}\), but the intercept on the x-axis (i.e. \(E\)) may be lower (see Singh et al. (1990) and Thakral et al. (1997) in Figure 2-6), possibly because of differences between monsoonal and Mediterranean climates. In Australia, experimental yields approximate the potential yield line (i.e. \(E = 110\) mm, \(T_e = 12.5\) kg ha\(^{-1}\) mm\(^{-1}\)), with irrigated yields at Tatura appearing to follow a diminishing return curve (Taylor et al. 1991). Mendham et al. (1984) attributed their very high yields to the moderate spring and early summer temperatures in Tasmania which allowed a long period for seed development at favourable radiation levels.

![Figure 2-6. Canola yield and water use data from published studies in which various levels of irrigation were applied.](image-url)
2.11 Wheat and canola comparative experiments

2.11.1 Yields

Hocking et al. (1997a) estimated that the net above-ground biosynthesis of 2.81 t ha\(^{-1}\) of glucose would produce 1 t ha\(^{-1}\) of wheat grain and 0.63 t ha\(^{-1}\) of oilseed grain and concluded that canola has a similar WP to wheat if it is sown early. This is in line with Holland et al. (1999) who found the ratio of canola to wheat yield converged on a value between 0.4 and 0.6 at high yield levels, though with greater variability at low yields.

2.11.2 Water use

Canola has been regarded as more susceptible to drought than wheat, its spring moisture requirement is said to be different and it is considered to have a high demand for water compared to cereal crops (Richards & Thurling 1978a; Buzza 1979; Colton & Sykes 1992). Krogman & Hobbs (1975) showed that the mean daily ET of rape and cereals was similar, but the total water requirement of canola was less because of its quicker maturity. In south-west Western Australia, Scott & Sudmeyer (1993) used the ventilated chamber technique to estimate seasonal ET, from daily measurements to show canola could be expected to use more water than wheat (430 mm compared to 346 mm) and ascribed this greater water use to deeper rooting and greater biomass production. Gregory (1998) and Angus et al. (1991) found total season water use was similar in dryland wheat and canola, with any difference being a reflection of maturity date rather than biomass. Gregory (1998) showed that canola used its water earlier in the season whilst wheat daily water use was nearly double that of canola by the end of the season.

There is evidence that biomass production in canola is more sensitive to water deficit (hence more responsive to irrigation) than in wheat (Morizet et al. 1984; Holland et al. 1999; Drecce et al. 2003). However, the opposite appears to be the case for yield, with canola yield less sensitive to water stress than wheat yield (Morizet et al. 1984). Holland et al. (1999) also suggested that canola yields were not as affected by terminal water deficit as wheat, based on their finding of a significant negative correlation across seasons between wheat HI and the ratio of canola to wheat yields. Additionally, reducing the number of irrigation’s has less effect on grain yield in canola than it does in wheat grown under similar conditions (Munoz & Fernandez 1978; Singh et al. 1989).
and significant differences in canola dry matter production do not translate into significant differences in grain yield or 1000 grain weight (Ward et al. 2002). This is different to the response in wheat where any reduction in spike dry weight reduces the number of kernels per unit area and hence grain yield (Acevedo et al. 2002).

Wheat is classified as a drought tolerant species (Musick & Porter 1990) and appears better adapted to dry conditions than canola. Hadjichristodoulou (1992) compared rapeseed and wheat yields in the Mediterranean climate of Cyprus and found that only wheat was successful in dry situations (total season water availability < 300 mm) because it maintained a larger HI. Adaptive mechanisms which regulate aquaporin activity in the cell membranes and restrict water flow at low water potential in wheat are absent in canola and canola root protoplast has a higher osmotic permeability (Morillon & Lassalles 2002). This may explain canola’s lower drought tolerance, as well as the earlier high water use found by Gregory (1998).

Canola has an earlier recommended sowing date than wheat (McRae, et al. 2004) and has a shorter time to flowering, though the total growing season lengths of the two crops are similar (Harbinson et al. 1986). Holland et al. (1999) believed that earlier maturity in canola relative to wheat would allow drought escape in the former and Gregory’s (1998) results indicate that earlier maturity should result in lower water requirement. Earlier flowering and maturation under more humid conditions when $T_e$ is higher and rainfall is more likely should allow drought escape and lower water requirement for canola in the Murray Valley, but no evidence of this was found in the literature.

2.11.3 Response to soil water conditions

Canola is considered to be relatively sensitive to waterlogging, particularly during the seedling stage and at flowering and a waterlogged site may achieve only 50% of the yield of a well drained site through the restriction of root development (Walton et al. 2003). In his review of the literature, Bernadi (1996) considered that canola appeared similar to wheat in its ability to withstand prolonged waterlogging under cold conditions, but advice to farmers in the irrigation districts of the southern MDB is that canola will not tolerate waterlogging, especially at flowering (Lolicato 2002). The effect of waterlogging on yields may be less in canola than in wheat because its indeterminate growth gives it the capacity to grow and flower over an extended period.
Cannell and Belford 1980). This is an advantage in erratic climates because the plant can form secondary shoots after a period of stress which may have caused fruiting or seed set to fail in a determinate plant such as wheat (Taiz and Zeiger 1991).

Zhang et al. (2004) observed that waterlogging during the vegetative phase in 2002 reduced shoot biomass by 27% and 40% in wheat and canola respectively compared to 2001, which was drier. Despite suffering a greater reduction in biomass, canola yields were 17% higher in 2002 whereas wheat yields were 37% lower. The authors attributed this difference to the ability of the (indeterminate) canola to respond to late rains in 2002 by significantly increasing the number of seeds per unit area. The (determinate) wheat, on the other hand, could not compensate for the earlier waterlogging induced reduction in ears per unit area, despite a 25% increase in grain size.

### 2.11.4 Root distributions and depths of water extraction

Weiss (1983) and Colton & Sykes (1992) state that canola is deeper rooted and has the ability to extract more water from depth than cereals and, in a survey of farmers and agronomists in NSW, Ryan et al. (2003) reported that respondents from drier regions repeatedly commented that canola extracted more soil water than other crops. At two sites in NSW (on a red-brown earth and a red gradational loam), Kirkegaard et al. (1997) found that canola roots grew to depths of about 1.8 m in two years, which was slightly deeper than wheat by about 10 cm in 3 of the 4 available comparisons. Holland et al. (1999) cited Kirkegaard, et al. (1997) and unpublished data and stated that the reported deeper rooting of canola compared to wheat (around 20 cm) may indicate a greater capacity of canola to utilise water from deeper soil layers. They note, however, that no published data is available to confirm this capacity.

Gregory (1998) grew a range of crops in a shallow, duplex soil with 30-40 cm sand overlying a dense clay subsoil. Only a few mm of water was extracted from the sub-soil by any of the crops and there was no evidence that tap-rooted legumes or oilseeds were better able than cereals to exploit subsoil water. He concluded that canola tap roots were not strong enough to exploit the dense subsoil at this site, supporting Cresswell & Kirkegaard’s (1995) finding of a lack of evidence for ‘biological drilling’ by canola in the B-horizon of dense, duplex soils. However, Rao & Mendham (1991b) observed moisture extraction by canola to 70 cm and below in a duplex soil with a heavy clay,
poorly structured subsoil and Taylor et al. (1991) observed water use from the 70-130 cm depth in duplex soils (Lemnos loam & Goulburn loam) with a shallow clay loam A horizon overlying a structure-less, massive clay B horizon.

Richards & Thurling (1978a) observed that a smaller root weight relative to the above ground plant weight and a heavier tap-root relative to lateral root was associated with higher canola seed yield. This is in contrast to the clear association between drought resistance and a more extensive root system in wheat (Hurd 1964; Hurd 1968). The negative association between yield and root/shoot ratio in their second paper (Richards and Thurling 1978b) was consistent with their earlier findings, though unexpected considering the generally accepted view of a larger root system being of considerable importance for plants growing under conditions of moisture stress.

2.12 Deep percolation and capillary upflow

Measurements of deep percolation and rates of capillary rise have been measured under a variety of crops grown on red-brown earths in the Riverina. Notable papers include those of Talsma (1963), Loveday & Scotter (1966), Loveday et al. (1978), Muirhead (1978) and Mason et al. (1983). Deep percolation over the growing season under a flood irrigated wheat crop varied from -6 mm (upflow) to 41 mm in the presence of a watertable at 1.5 to 2.1 m, being greatest in unirrigated plots and least in plots frequently irrigated at 90% PAW (Steiner et al. 1985). Using sprinkler irrigation at the same site, Meyer et al. (1987) found evidence that upward flux from the water-table contributed up to 30% of daily ETc from a wheat crop, even though deep percolation was 49 to 81 mm over the whole season when irrigating at 50 to 75% of PAW.

In the winter rainfall areas of southern Australia, the amount of deep percolation in winter is directly related to the root-zone soil-water content in autumn (O'Connell et al. 2003; Whitfield 2001). Humphreys et al. (2001; 2003) have observed that wheat planted straight after rice can reduce deep percolation and improve WP in the rice farming system. The benefits of sowing crops other than wheat after rice was not examined and, in their review of the literature pertaining to deep percolation and crop water use of irrigated annual crops and pastures in Australia, Humphreys et al. (2003) found no published work that examined deep percolation below canola crops.
2.13 Conclusions

The impact of increasing competition for finite water resources in the MDB is expected to be greatest upon farmers in the Murray Valley who irrigate low value annual crops and pastures. For these farmers, improving WP presents a challenge, as conventional strategies involve raising large amounts of capital which increases their exposure to risk for an uncertain outcome. It has been suggested that improving profitability is a more appropriate objective for individual farm businesses than increasing WP and this will be achieved by finding more profitable production functions.

The actual relationship between $Y$ and $W_A$ is interpreted as being determined by $E$, $T_e$ and $I_e$ so, for a given crop and locality, more profitable production functions will be obtained by decreasing $E$ and increasing $T_e$ and $I_e$. It is concluded that improving the production functions of winter crops provides greater opportunity for maintaining farm profitability when water is limited than trying to improve the production functions of summer crops, particularly rice. If water is limiting, profits are maximised by selecting the crop with the greatest response to irrigation and applying less than is required to achieve maximum yields. The actual irrigation depth applied will depend on commodity prices and the relevant costs of production.

A number of examples were found in the literature where production functions were used to determine optimal irrigation strategies for wheat, particularly in Syria and China. In the southern MDB, production functions for wheat were obtained by Cooper (1980b) and for barley by Gyles (2001), but no examples could be found for canola. A number of canola studies did include deficit irrigation treatments, but only one of these (Taylor et al. 1991) was conducted in the southern MDB and there was not enough information to derive a production function. Additionally, Robinson (2004) stated that none of the field data sets he used, which included wheat, incorporated yield responses to various levels of water deficit. This overlooking of Cooper’s (1980b) results, as well as Steiner et al.’s (1985) scepticism of them, indicates they need verifying for the southern MDB.

Deficit irrigation is a recommended practice for both wheat and canola in the Murray Valley when irrigation water is limited. Wheat’s drought tolerance makes it well suited to deficit irrigation, but canola’s suitability is less clear. There is evidence that canola biomass production is more sensitive to drought than wheat and that canola yields are
related to the amount of biomass at flowering. However, there is also evidence that its indeterminate growth makes canola grain yield less sensitive to drought than wheat, and earlier sowing, flowering and harvest may permit drought avoidance. Whilst the recommended deficit irrigation strategies are based upon well known yield responses in the case of wheat, there is scant evidence to support its practice in canola. Furthermore, grower experience suggests that the lack of response of canola makes spring irrigation unjustifiable in the NSW Murray Valley. If the production function is a diminishing return curve, then the first irrigation is the most profitable, but the question remains as to which crop should receive this irrigation when water is limiting.

The literature review also highlighted the complete lack of evidence to support values given in advisory publications for local crop factors for canola. Furthermore, the presumption that canola growth stage lengths are similar to wheat requires further examination given that canola has a slower initial growth rate and an earlier time to flowering than wheat. Crop phenology models may provide a means of predicting growth stage lengths for both wheat and canola, particularly the timing of flowering and physiological maturity. If used in conjunction with historical climate data, Stapper & Fischer’s (1990a) wheat model and Robertson et al.’s (1999) canola model offer a means of determining the probability of drought at critical times during the growing season as well as the expected maximum irrigation requirement given a range of sowing dates. Neither model has been tested on crops in the Murray Valley.

The benefits of growing wheat after rice to reduce groundwater accessions and improve WP in the rice farming system have been established. There is evidence that canola is deeper rooted and has a higher water use than wheat, particularly early in the season, so canola may have a greater ability to reduce groundwater accessions in the rice rotation. However, no evidence was found to confirm this and no publication shed any light on the deep percolation component of the water balance for canola. There were questions raised in the literature regarding the ability of canola roots to penetrate dense subsoils, particularly during drought, as well as the sensitivity of canola to waterlogging at the seedling and flowering stages. The potential for canola to extract more water than wheat from the soil profile requires investigation. This investigation needs to show canola can be sown and established in typical rice irrigation layouts and soils, under wet soil conditions similar to those which can occur in autumn in the Murray Valley.
Chapter 3. Materials and Methods

3.1 The experimental site

The experiments reported here were conducted at NSW Agriculture’s Murray Valley Field Station (35°30’ S 145°18’ E, elevation 95 m), 10 km north east of Deniliquin. The site is centrally located within the Murray Irrigation districts of southern NSW and is considered to contain soils representative of these districts. Irrigation water (0.04 – 0.06 dSm\(^{-1}\); Murray Irrigation Limited 2003) is supplied from the Murray River at Mulwala through the Murray Irrigation Ltd channel system.

Two separate sites were used in this experiment: Block 25 Bay E (Site 1) and Block 30 Bay A (Site 2). Both Blocks were land-formed and laid out for border check irrigation in 1987. Site 1 had a slope of 1 in 1000 and Site 2 a slope of 1 in 500.

3.1.1 The experimental areas

An electromagnetic induction survey (Geonics\textsuperscript{TM} EM38) of both sites was conducted to assess soil spatial variability prior to finalising the experimental design (Johnson et al. 2001; Johnson et al. 2003). The results of these surveys are shown in Figure 3-1. In both cases the experiments were located to avoid large soil variations and designed so that similar areas occurred within blocks. In Site 1 it was considered important to confine the experiment to one irrigation bay (the most uniform) and avoid an old channel and leakage from the farm supply along 140 m of the western boundary. The soil in Site 2 had a lower EC\(_a\) (i.e. lighter textured) and was more variable. An area of high EC\(_a\) (i.e. heavy textured soil) at the bottom of this bay was avoided.

3.1.2 Soil characteristics

The soil at both sites has been classified as a red-brown earth (Stace, et al. 1968), but there are marked differences between the soils in Site 1 and Site 2. The soil in Site 1 is a Subnatric Calcic Red Sodosol (Isbell 1996), Dr 2.13 (Northcote 1979), known locally as a Birganbigil Loam (Smith 1945). It has only fair surface and internal drainage and is
classified as suitable for growing rice. The results of chemical and physical tests conducted on soil from within the 1998 experimental area in Site 1 are shown in Table 3-1 and the physical characteristics of each horizon are shown in Figure 3-2.

Figure 3-1. Contour maps showing the results of the EM38 survey of (left) Site 1 (Bays 25E1 and 25E2) and (right) Site 2 (Bay 30A) together with the location and the layout of the experimental plots in 1998 (Site 1a = 25E2) and 1999 (Site 1b = 25E1; Site 2 = 30A). Readings of apparent electrical conductivity (ECa) are from the EM38 in the vertical dipole mode and have the units of mS m⁻¹. Site 1 (Bay 25E) was surveyed on 24/3/1998 and Site 2 (Bay 30A) on 11/3/1999.
Table 3-1. Selected soil properties of the Birganbigil loam from four depths in Site 1a (Bay 25E2).

Values are the means of three samples, with standard deviations shown in brackets.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Sand (1) &gt;20 µm (%)</th>
<th>Silt (1) 2-20 µm (%)</th>
<th>Clay (1) &lt; 2 µm (%)</th>
<th>Dry Bulk Density (g cm(^{-3}))</th>
<th>Particle Density (2) (g cm(^{-3}))</th>
<th>pH (3)</th>
<th>EC(_{se}) (dS m(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>52.1 (2.6)</td>
<td>23.9 (0.6)</td>
<td>24.0 (2.4)</td>
<td>1.36 (0.02)</td>
<td>2.65 (0.04)</td>
<td>6.0 (0.2)</td>
<td>0.9 (0.1)</td>
</tr>
<tr>
<td>30-40</td>
<td>28.4 (2.1)</td>
<td>18.4 (2.1)</td>
<td>53.2 (2.6)</td>
<td>1.59 (0.01)</td>
<td>2.72 (0.01)</td>
<td>8.1 (0.2)</td>
<td>1.1 (0.1)</td>
</tr>
<tr>
<td>50-60</td>
<td>31.0 (1.3)</td>
<td>22.5 (2.5)</td>
<td>47.5 (1.9)</td>
<td>1.60 (0.01)</td>
<td>2.73 (0.01)</td>
<td>8.9 (0.1)</td>
<td>2.0 (0.2)</td>
</tr>
<tr>
<td>90-100</td>
<td>22.0 (1.4)</td>
<td>37.0 (5.7)</td>
<td>41.0 (5.1)</td>
<td>1.59 (0.01)</td>
<td>2.74 (0.01)</td>
<td>8.8 (0.3)</td>
<td>5.5 (0.4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Cl (5) cmol(-)kg(^{-1})</th>
<th>Ca (6) cmol kg(^{-1})</th>
<th>Mg cmol kg(^{-1})</th>
<th>Na cmol kg(^{-1})</th>
<th>K cmol kg(^{-1})</th>
<th>CEC (7) cmol kg(^{-1})</th>
<th>ESP (8) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>0.08 (0.01)</td>
<td>4.4 (0.1)</td>
<td>3.0 (0.6)</td>
<td>0.60 (0.23)</td>
<td>0.60 (0.10)</td>
<td>13.8 (0.6)</td>
<td>7</td>
</tr>
<tr>
<td>30-40</td>
<td>0.29 (0.03)</td>
<td>7.8 (0.6)</td>
<td>9.8 (0.8)</td>
<td>2.0 (0.8)</td>
<td>0.81 (0.16)</td>
<td>22.6 (1.2)</td>
<td>9</td>
</tr>
<tr>
<td>50-60</td>
<td>0.82 (0.11)</td>
<td>6.9 (0.6)</td>
<td>11.0 (0.3)</td>
<td>2.8 (1.2)</td>
<td>0.66 (0.16)</td>
<td>22.1 (1.3)</td>
<td>13</td>
</tr>
<tr>
<td>90-100</td>
<td>3.48 (0.27)</td>
<td>4.9 (0.6)</td>
<td>10.9 (1.5)</td>
<td>4.3 (0.8)</td>
<td>0.59 (0.05)</td>
<td>21.0 (1.7)</td>
<td>21</td>
</tr>
</tbody>
</table>

1. Pipette method (Gee & Or 2002)
2. Volumetric flasks used in liquid displacement method (Flint & Flint 2002)
4. Electrical conductivity of saturated paste extract (Slavich & Petterson 1993)
5. Coulometric titration (Buchler-Cotlove chloride meter) of saturated paste extract (Slavich & Petterson 1993)
8. Exchangeable sodium percent calculated from (Exch. Na/sum Exch. cations) × 100

Figure 3-2. Characteristic properties of the Birganbigil loam at Site 1.
The soil at Site 2, is a *Brown Chromosol* (Isbell 1996), Dr 3.13 (Northcote 1979), known locally as a Cobram loam (Smith 1945). It is a lighter textured soil than the Birganbigil Loam, with a slightly deeper A horizon and a pronounced fine sandy clay B2 horizon (Table 3-2). It has a higher proportion of coarse sand at all depths, giving it good internal drainage and making it unsuitable for growing rice. The topsoil at Site 2 is relatively uniform, but there is considerable variation in subsoil texture across the site (Figure 3-1).

**Table 3-2. Particle size analysis of the Cobram loam (from Slavich et al. 2002).**

<table>
<thead>
<tr>
<th>Soil Horizon</th>
<th>Depth (cm)</th>
<th>Sand &gt;20 µm %</th>
<th>Silt 2-20 µm %</th>
<th>Clay &lt; 2 µm %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0-15</td>
<td>50.7</td>
<td>26.3</td>
<td>23.4</td>
</tr>
<tr>
<td>B1</td>
<td>15-45</td>
<td>29.5</td>
<td>23.7</td>
<td>41.8</td>
</tr>
<tr>
<td>B2</td>
<td>45-70</td>
<td>40.5</td>
<td>41.0</td>
<td>16.5</td>
</tr>
<tr>
<td>C</td>
<td>&gt;70</td>
<td>18.6</td>
<td>44.5</td>
<td>34.2</td>
</tr>
</tbody>
</table>

### 3.2 Treatments and experimental design

Wheat (W) var. Janz and canola (C) var. Oscar were grown in both 1998 and 1999. To assess the water requirements and the effects of deficit irrigation in spring on the two crops, four irrigation strategies (I) were compared in both years: (1) unirrigated in spring; (2) one spring irrigation; (3) deficit irrigation when the cumulative evaporation minus rainfall (\(E-P\)) deficit was 90 mm; and (4) full irrigation when the \(E-P\) deficit was 60 mm. Crop (W or C) and irrigation (I) treatments are denoted by the subscripts 0, 1, Def and Full respectively. Dates when treatments were irrigated are shown in Table 3-3.

The commonly accepted irrigation interval for the soils in this experiment is 50 to 60 mm \(E-P\) (Cockroft & Martin 1981; Wright et al. 1988; Taylor et al. 1991). Infiltration studies on the Birganbigil loam at Site 1 indicated that approximately 50 mm will infiltrate in the high rate phase and 60 mm after 90 minutes (Hume 1993). The Cobram loam at Site 2 is lighter textured and “deeper”, so 60 mm \(E-P\) was considered an appropriate irrigation interval for the full irrigation treatments at both sites (Cockroft & Martin 1981). A \(K_c\) of 1 was assumed for both crops for the purposes of scheduling irrigations in these experiments. This was decided because of the uncertainty associated
with the values of $K_c$ for canola and because it was likely to ensure that the full irrigation treatments were not water stressed. Consequently, $E$ was equivalent to $ET_o$ and this was calculated from weather data collected on the Field Station using the Penman-Monteith equation.

The first spring irrigation of the crops at Site 1 was timed to occur when the $E-P$ deficit had drawn down to 60 mm from the “full” profile in mid winter (21st July 1998; 23rd July 1999). At Site 2, an $E-P$ deficit of 90 mm was used for the first spring irrigation because of the lighter texture and greater depth in the B horizon. Visual assessments of the crops (i.e. leaf temperature, colour changes, signs of wilting) were done to confirm the timings of the first irrigation in both years and these were supported by pressure chamber measurements of leaf water potential in 1998.

Table 3-3. Details of the dates when the wheat (W) and canola (C) treatments were irrigated at Site 1a in 1998 (top), Site 2 in 1999 (middle) and Site 1b in 1999 (bottom). X indicates irrigation.

<table>
<thead>
<tr>
<th>1998</th>
<th>Site 1a</th>
<th>Pre-irrigation</th>
<th>8/9 Sept</th>
<th>10 Oct</th>
<th>16 Oct</th>
<th>24 Oct</th>
<th>5 Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_0^2$ &amp; $C_0$</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_1$ &amp; $C_1$</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_{Def}$ &amp; $C_{Def}$</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_{Full}$ &amp; $C_{Full}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 three autumn irrigations were applied: 4 Mar, 10 Mar and 2 June
2 $0 = no spring irrigation; 1 = 1 spring irrigation; Def = deficit irrigation; Full = full irrigation

<table>
<thead>
<tr>
<th>1999</th>
<th>Site 2</th>
<th>25 Feb</th>
<th>18 Sep</th>
<th>16 Oct</th>
<th>22 Oct</th>
<th>11 Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_0$ &amp; $C_0$</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_1$ &amp; $C_1$</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_{Def}$ &amp; $C_{Def}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{Full}$</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_{Full}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1999</th>
<th>Site 1b</th>
<th>4 Mar</th>
<th>3 Sep</th>
<th>23 Sep</th>
<th>20 Oct</th>
</tr>
</thead>
</table>

In 1998, the experimental design in Site 1a (Bay E2 in Block 25; Figure 3-1) was a randomised block, with three blocks across the irrigation bay and eight plots per block (Table 3-4). The ECa contours run parallel to the length of the irrigation bay in Site 1a (Figure 3-1), so blocking in this way minimised with-in block soil variation. Plots were 12.5 m long by 7 m wide with a 2 m buffer between adjacent plots.
The soil in Site 2 was more variable, so four replicates were used in a split-plot design at this site in 1999 (Table 3-5) with the aim to minimise with-in plot soil variation (Figure 3-1). Sub-plots were 19 m by 9 m with a 2 m buffer. To enable a direct comparison of crop performance at Sites 1 and 2, Site 1b was also sown to wheat and canola in 1999. Plots at Site 1b were 15 m wide by 30 m long (Figure 3-1) and there were four replicates in a randomised block design (Table 3-5). Different irrigation treatments were not applied and the whole bay (all plots) received full irrigation at an E-P deficit of 60 mm. The timing of irrigations at Site 1b and Site 2 in 1999 was different (Table 3-3) because spring irrigation commenced two weeks earlier at Site 1b.

Table 3-4. The randomised block design used in Site 1a in 1998.

<table>
<thead>
<tr>
<th>Block</th>
<th>Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>W&lt;sub&gt;Full&lt;/sub&gt;</td>
<td>C&lt;sub&gt;0&lt;/sub&gt;</td>
</tr>
<tr>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
<td>W&lt;sub&gt;0&lt;/sub&gt;</td>
</tr>
<tr>
<td>W&lt;sub&gt;1&lt;/sub&gt;</td>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>W&lt;sub&gt;Def&lt;/sub&gt;</td>
<td>C&lt;sub&gt;Full&lt;/sub&gt;</td>
</tr>
<tr>
<td>C&lt;sub&gt;Full&lt;/sub&gt;</td>
<td>C&lt;sub&gt;Def&lt;/sub&gt;</td>
</tr>
<tr>
<td>C&lt;sub&gt;0&lt;/sub&gt;</td>
<td>W&lt;sub&gt;Def&lt;/sub&gt;</td>
</tr>
<tr>
<td>C&lt;sub&gt;Def&lt;/sub&gt;</td>
<td>W&lt;sub&gt;Full&lt;/sub&gt;</td>
</tr>
<tr>
<td>W&lt;sub&gt;0&lt;/sub&gt;</td>
<td>W&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Table 3-5. The split-plot experimental design used at Site 2 in 1999 (left) and the randomised block design used at Site 1b in 1999 (right).
3.3 Cultural practices

Site 1a had two years of sub-clover (*Trifolium subterranean*) based annual pasture prior to 1998. The site was top-dressed on 2\textsuperscript{nd} March 1998 with single super-phosphate at 150 kg ha\textsuperscript{-1} (13.2 kg P ha\textsuperscript{-1} and 16.5 kg S ha\textsuperscript{-1}) and pre-irrigated twice (4\textsuperscript{th} and 10\textsuperscript{th} March). This germinated the pasture, which was sprayed with 1.5 L ha\textsuperscript{-1} Roundup\textsuperscript{®} (360 g L\textsuperscript{-1} glyphosate) on 9\textsuperscript{th} & 27\textsuperscript{th} April to give a weed-free seedbed.

Both Site 1b and Site 2 had three years of annual pasture prior to 1999. Both sites were pre-irrigated (25\textsuperscript{th} February for Site 2 and 4\textsuperscript{th} March for Site 1b) and then disc cultivated (5\textsuperscript{th} March for Site 2 and 11\textsuperscript{th} March for Site 1b) to provide a conventionally cultivated seed bed. This change in seed bed preparation was done to avoid the crusting which had affected canola emergence in 1998. 2 L ha\textsuperscript{-1} of Treflan\textsuperscript{®} (125 g L\textsuperscript{-1} trifluralin) and 3 L ha\textsuperscript{-1} of Sprayseed\textsuperscript{®} (135 g L\textsuperscript{-1} paraquat and 115 g L\textsuperscript{-1} diquat) were applied in one application and incorporated into the seed bed two hours later in both blocks just prior to sowing (26\textsuperscript{th} May).

The wheat and the canola were sown into moist soil on 2\textsuperscript{nd} May in 1998 and 27-28\textsuperscript{th} May in 1999 using a 13 row linkage mounted John Shearer direct drill combine (T-boot sowing tines and light harrows). Row spacing was 0.18 m. The wheat was sown 2.5 cm deep at a rate of 150 kg ha\textsuperscript{-1} in 1998 and 130 kg ha\textsuperscript{-1} in 1999. The sowing rate was reduced in 1999 because the plant population at establishment in 1998 had been too high (251 plants m\textsuperscript{-2} in 1998 compared to a recommended density for irrigated crops of 150-200 plants m\textsuperscript{-2}; Varley \textit{et al.} 1999). The canola was sown 1 cm deep at a rate of 6 kg ha\textsuperscript{-1} in both years. 100 kg ha\textsuperscript{-1} di-ammonium phosphate fertiliser was applied with the seed to both crops (equivalent to 18 kg N ha\textsuperscript{-1}, 20 kg P ha\textsuperscript{-1} and 2 kg S ha\textsuperscript{-1}).

To prevent red-legged earth mite damage to the emerging canola, the trial areas (plus an 18 m buffer strip) were sprayed with 150 mL ha\textsuperscript{-1} LeMat\textsuperscript{®} (omethoate 580 g L\textsuperscript{-1}) within one week of sowing. In 1998, 2.1 L ha\textsuperscript{-1} of Thiodan\textsuperscript{®} (endosulfan 350 g L\textsuperscript{-1}) was applied on the 24 July to the canola plots to control brown pasture looper (*Ciampa arietaria*) and common cutworm (*Agrostis infusa*).

Herbicides were used to control post emergent weeds. In 1998, all plots were sprayed with 1 L ha\textsuperscript{-1} of Hoegrass \textsuperscript{®} (*diclofop methyl* 375 g L\textsuperscript{-1}) on 17\textsuperscript{th} June to control grass
weeds, primarily annual ryegrass (*Lolium rigidum*). The canola plots were sprayed again for grass weeds on the 12th July with 0.5 L ha\(^{-1}\) Fusilade® (*fluazifop-p* 212 g L\(^{-1}\)).

In 1999, the wheat plots were sprayed with 1 L ha\(^{-1}\) Tigrex® (250 g L\(^{-1}\) MCPA, 25 g L\(^{-1}\) *Diflufenican*) on 19th August to control broadleaf weeds. Unfortunately, overspray setback the majority of the wheat in plots B-5 and B-6 in Site 2 (i.e. rep 3 of W\(_0\) and W\(_{Full}\)) and approximately half the crop in these plots later died. Whilst measurements were still made in these plots following this incident, they have been treated as missing plots because of the detrimental effect of the herbicide. The rest of the wheat was unaffected and no damage from drift was observed in the canola.

All wheat and canola plots were top-dressed by hand with 100 kg ha\(^{-1}\) of Urea (46 kg N ha\(^{-1}\)). This took place on 5th August in 1998 and 17th August in 1999 and was timed for the end of tillering in the wheat (DC30; Tottman & Broad 1987) and stem extension and start of flower bud development in the canola (SM 2.5-3.0; Sylvester-Bradley & Makepeace 1984).

Although 11.5 mm of rain fell the night following sowing in 1998, very dry conditions for the rest of May necessitated an irrigation on 2nd June. Measurement of soil water contents before and after this irrigation showed the addition of 36 mm to the profile (0-1.3 m), filling it prior to the onset of the winter period and (fortuitously) simulating conditions which occur following a rice crop. Ditch-banks were formed down the length of the bays once the crops were well established (13 June in 1998; 17 August in 1999) and then across the bays in Site 1a and Site 2 a week prior to the first spring irrigation.

### 3.4 Agronomic measurements

#### 3.4.1 Crop development

Plants were examined to assess crop development when samples were taken for growth analysis. The stage of crop development was described according to published growth keys: Tottman & Broad (1987) for the wheat and Sylvester-Bradley & Makepeace (1984) for the canola. Throughout this document, the codes for the two crops are differentiated by the labels DC and SM for the wheat and canola respectively.
### 3.4.2 Analysis of growth

Establishment counts were made when the plants of both crops were at the 4 leaf stage. In 1998, seedlings in 0.36 m$^2$ (2 rows $\times$ 1 m) were counted on the 1$^{\text{st}}$ June (30 DAS) in all wheat plots. Canola seedlings were counted on the 3$^{\text{rd}}$ July (62 DAS) but, as soil crusting affected emergence, a larger area (2.34 m$^2$ =13 rows $\times$ 1 m) was sampled to account for greater variability. In 1999, seedlings were counted on the 16$^{\text{th}}$ July (50 DAS) in 0.72 m$^2$ (4 rows $\times$ 1 m) in both the wheat and canola plots.

In 1998 and 1999 all plots were sampled for dry biomass at the end of tillering and flowering in the wheat; the beginning of flower bud development and peak flowering in the canola; and physiological maturity (PM) in both. This corresponded to growth stages DC30, DC61 and DC87$^1$ in the wheat and SM3.1, SM4.5 and SM6.9 in the canola. To help define crop growth curves, additional plant samples were taken in Site 1 when time allowed in 1998 and at (mostly) fortnightly intervals in 1999. Plants were cut at ground level, bagged and transported to the laboratory for processing. In 1998, 2 rows by 1 m (0.36 m$^2$) were sampled from the wheat and 4 rows by 1 m (0.72 m$^2$) from the canola on most sample dates. The larger plots used in 1999 allowed 6 rows by 1 m (1.08 m$^2$) to be sampled from both the wheat and the canola. To minimise any edge effects, all samples were taken at least 1 metre away from the plot edge.

For all samples, the number of plants/tillers was counted and then the leaves were pulled off the stems/tillers and fed into an electronic planimeter (Paton Scientific, Adelaide) to determine green leaf area (one sided). Stems, wheat heads and canola buds/flowers/pods were not measured with the planimeter. The green leaf area (GLA) of the whole sample was measured early in the season but, as sample size increased, a sub-sample of leaves from 50 wheat tillers or 10 canola plants was measured. Total sample dry weight was determined after drying in a fan forced dehydrator at 65°C for 48 hours.

---

$^1$ Stapper and Fischer (1990a) describe PM as occurring at DC86. Tottman and Broad (1987) define DC87 as “Hard dough … finger nail impression is held … maximum dry weight” and this definition is followed in this thesis. Where DC86 is used, it is a direct quote from Stapper and Fischer (1990a) and is considered synonymous with DC87.
3.4.3 Yield, yield components and harvest index

Final dry matter cuts were made at assessed PM. Plants were cut at ground level from a 1.08 m² area (6 rows by 1 m) and bagged to catch any grain that shelled out. Samples were dried, weighed and the number of plants or spikes in each sample was counted. In the canola, the number of pods on a sub-sample of 10 plants was counted. Samples were threshed and cleaned and the grain weight recorded.

Once the crops had ripened, header strips (1.6 m wide) were taken with a small plot harvester (Kingaroy Engineering Works). The ends of each plot were harvested to remove plants subjected to edge effects and the distance between these trimmed ends measured. The canola was harvested before the wheat in both years (Table 3-6), making it possible to strip all four irrigation treatments in the canola before any of the header settings needed to be changed for the wheat.

Table 3-6. Harvest dates for each treatment in 1998 and 1999.

<table>
<thead>
<tr>
<th></th>
<th>1998 Harvest Date</th>
<th>1999 Harvest Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₀ &amp; C₁</td>
<td>16ᵗʰ Nov</td>
<td>C₀</td>
</tr>
<tr>
<td>CₐDef &amp; CₐFull</td>
<td>20ᵗʰ Nov</td>
<td>C₁, CₐDef &amp; CₐFull</td>
</tr>
<tr>
<td>All wheat</td>
<td>27ᵗʰ Nov</td>
<td>All wheat</td>
</tr>
</tbody>
</table>

The grain samples from the header were weighed and two sub-samples (≈ 300 g) were taken. One sub-sample was used to obtain grain moisture contents for converting the harvested yields to standard moisture contents: 12% for wheat and 8.5% for the canola. The second sub-sample was used to obtain the 1000 grain weight and then analysed for oil content (canola) or protein (wheat) using near infra-red spectroscopy.

Grain yield and grain weight from the header samples were used with spikes m⁻¹ from the final dry matter cuts to calculate grains per spike for each wheat plot.
3.4.4 Plant water potential

To assess the affect of the irrigation treatments on plant water status, dawn plant water potential was measured using a pressure chamber (PMS Instrument Co.) prior to each spring irrigation in Site 1a in 1998. The dates, times and treatments sampled are shown below in Table 3-7. Additional sampling to assess maximum plant moisture stress was done at mid-day on the 18th September and the 15th October when the crops in the C₀ and W₀ plots were visibly stressed.

The top 15 cm of the flag leaf was sampled in the wheat and branch water potential was measured in the canola, with the top 20 cm of the main stem containing pods, flowers and buds (not leaves) sampled (Bernadi 2000). Plant parts were wrapped in a damp paper towel and placed in a plastic bag prior to cutting them from the plant with a scalpel. The samples were placed in an esky cooled by ice “bricks” and transported to the field laboratory for measurement. Six random samples were taken from each plot in the treatments assessed and all sampling was completed within a one hour period. It was noted that dew was present on the crops every time samples were collected at dawn.

Table 3-7. The dates, times and treatments sampled for plant water potential in Site 1a, 1998.

<table>
<thead>
<tr>
<th>Sample Date</th>
<th>Sample Time</th>
<th>Treatments Sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>8th Sept</td>
<td>7:45 – 8:45 am</td>
<td>C, W</td>
</tr>
<tr>
<td>18th Sept</td>
<td>1:00 – 2:00 pm</td>
<td>C₀, W₀, C₁, Def, Full, W₁, Def, Full</td>
</tr>
<tr>
<td>30th Sept</td>
<td>7:30 – 8:00 am</td>
<td>C₀, W₀, CFull, WFull</td>
</tr>
<tr>
<td>10th Oct</td>
<td>6:30 – 7:00 am</td>
<td>CFull, WFull</td>
</tr>
<tr>
<td>15th Oct</td>
<td>6:30 – 7:30 am, 1:00 – 1:45 pm</td>
<td>C₀, W₀, CDef, WDef, CFull, WFull</td>
</tr>
<tr>
<td>23rd Oct</td>
<td>6:00 – 7:00 am</td>
<td>C₀, W₀, C₁, W₁, CFull, WFull</td>
</tr>
</tbody>
</table>

The procedure and precautions followed in the field laboratory were as described by Turner (1988). Specifically, samples were removed from the plastic bags and placed in the pressure chamber which was lined with damp paper towel to prevent evaporative water loss. The chamber was pressurised with Nitrogen gas at a rate of 0.02 MPa s⁻¹ and ‘flooding’ of the cut surface was observed through a magnifying glass and a hand lens.
3.5 Hydrologic measurements

To determine crop factors and to assess the comparative ability of the two crops to capture deep soil moisture, a range of hydrological measurements were made on the crops in Site 1a in 1998. The same level of detailed monitoring was not done in 1999.

3.5.1 Weather Data

Meteorological data was collected by an automatic weather station located 800 m south of the experimental site. Wet and dry bulb temperature, solar radiation and wind run at 2 m were recorded. Rainfall ($P$) was measured by a tipping bucket rain gauge (0.2 mm per tip, 200 mm diameter). Pan evaporation ($E_{pan}$) data was from the Bureau of Meteorology class A pan located at Deniliquin airport, 15 km from the experimental site.

Allen, et al. (1998) describe a number of factors which produce differences between $E_{pan}$ and the reference crop evapotranspiration ($ET_o$) and recommend local calibration of $E_{pan}$ against $ET_o$ computed with the Penman-Monteith method. This was done for the Bureau of Meteorology Class A pan at Deniliquin using data from the period January 1998 to June 2003. Assuming a linear relationship, the pan coefficient ($K_p$) was found to be 0.72 ($R^2 = 0.97$, P<0.001, se = 0.425). However, the power function

$$ET_0 = 0.88 \times (E_{pan})^{0.91}$$

Equation 3-1

fitted the data better ($R^2 = 0.98$, P<0.001, se =0.355) over the entire data range and was adopted for use in this study (see Appendix A).

3.5.2 Soil water content

Volumetric soil water content ($\theta_v$) was measured with a Campbell Pacific Nuclear model 503 neutron moisture meter (NMM) inserted in an aluminium access tube (46 mm external diameter and 1.6 mm wall thickness). Readings ($n$ = one 16 second count) were taken at 10, 20, 30 and 40 cm and then every 20 cm to 1.2 m. A standard count in water ($N$ = mean of sixteen 16 second counts) was obtained each day readings were taken and the count ratio ($C_R = n/N$) determined. Surface soil readings were obtained by laying the NMM probe on the soil surface within a hydrogenous shield (Chanasyk &
Access tubes were installed in each plot after the crops had been sown in Site 1a in May 1998. The first readings were taken on 29th May and then every two to three days, following rainfall and immediately prior to and the day following irrigation. In 1999, access tubes were only installed in spring in I₀ and Iᵋ treatments in Site 2 but not at all in Site 1b.

Calibration equations were derived for Site 1a to convert $C_R$ values from each depth to $\theta_v$. Separate linear relationships were obtained for each depth: slope and intercept parameters are shown in Table 3-8. The soil was more variable in Site 2 (Figure 3-1), so rather than obtaining absolute values of $\theta_v$, a previously determined ‘universal’ slope of 0.711 (Verbyla & Cullis 1992) was adopted to measure the change in $\theta_v$.

### Table 3-8. Parameters of the NMM calibration equations for each depth of reading in Site 1a

<table>
<thead>
<tr>
<th>Depth of Reading (cm)</th>
<th>Bulk Density (g cm⁻³)</th>
<th>Regression of $\theta_v$ on $C_R$ slope</th>
<th>intercept</th>
<th>$R^2$</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface</td>
<td>1.26</td>
<td>-0.432</td>
<td>0.944</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.47</td>
<td>-0.024</td>
<td>0.977</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.59</td>
<td>-0.007</td>
<td>0.981</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1.57</td>
<td>-0.074</td>
<td>0.982</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1.60</td>
<td>-0.152</td>
<td>0.971</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>1.60</td>
<td>-0.157</td>
<td>0.845</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>≥ 75</td>
<td>1.59</td>
<td>-0.035</td>
<td>0.827</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

Profile water contents to 1.0 m were calculated from the $\theta_v$ data using:

$$S = 50 \times \theta_v + 100 \times (\theta_{s10} + \theta_{s20} + \theta_{s30} + \theta_{s100}) + 150 \times \theta_{s40} + 200 \times (\theta_{s60} + \theta_{s80})$$

Equation 3-2

where $S$ is the profile water content (mm), the subscript $s$ refers to the surface soil reading and the subscripts 10, 20, 30 etc refer to the depths of reading in cm.

### 3.5.3 Soil water potential

Soil water potential was measured at 80, 100 and 120 cm in I₀, Iᵋ and Iᵋᵋ treatments in Site 1a in spring 1998 using puncture tensiometers which were read using a portable vacuum gauge (LOK, New Zealand). Following Goodwin (1995), the tensiometers were constructed from electrical conduit and porous ceramic cups (50 mm by 20 mm OD).
which had a bubbling pressure of approximately -100 kPa (Cooinda Ceramics Pty Ltd). A limited number of available porous cups meant that the $I_{\text{def}}$ was not instrumented.

Tensiometers were checked and installed in early August 1998 following the procedures described by Goodwin (1995); except that installation holes were made using a thin wall sampler (30 mm OD) rather than an auger and backfilled using dry bentonite. The three tensiometers in each plot were installed 15 cm from each other in a triangular arrangement centred approximately 1.0 m from the NMM access tube. Readings commenced on the 20th August and were made using the double puncture technique (Greenwood & Daniel 1996) on the same days the NMM was read. All tensiometers were serviced twice during the season; 31st August and 27th October.

Tensiometer readings, in millibars ($mbar$), were converted to head of water ($h$) and matric ($\psi_m$) and total hydraulic ($H$) potential according to:

$$h = \frac{-mbar}{9.807} \times 10$$  
Equation 3-3

$$\psi_m = h + G$$  
Equation 3-4

$$H = \psi_m + z$$  
Equation 3-5

where $G$ is the length of the water column in the tensiometer, $z$ is the depth of the centre of the tensiometer cup below a reference level (i.e. the soil surface) with units in centimetres. Readings greater than 800 mbar were considered beyond the limit of reading of the tensiometer (Bond 1998) and were discarded.

### 3.5.4 Irrigation

#### Autumn Irrigations

For the autumn irrigations water was applied to the whole irrigation bay, not just the experimental site. The volume of water was not measured and it was assumed that the irrigation water was uniformly applied to the whole site. This assumption is reasonable given that both sites were in laser-graded irrigation bays that were designed to ensure good distribution uniformity. The assumption was confirmed in Site 1a by the small variation in the $C_R$ values obtained from NMM readings in all plots after the third
autumn irrigation on the 2\textsuperscript{nd} June (the coefficient of variance for the readings at 10 cm was 4.4\% and the average for all depths was 3\%).

\textbf{Spring Irrigations}

Water was pumped onto plots through portable irrigation pipe and the applied volume was measured by an in-line propeller flow meter (Arad type M2). Where possible, a depth of water equivalent to the \(E-P\) deficit (i.e. 60 or 90 mm) was applied to each plot. Irrigation of a plot was stopped before this if it appeared water would overtop the bank and extra water was applied when necessary to ensure coverage by at least 10 mm of water over the entire plot surface. The dimensions of the wetted area in each plot were measured after each irrigation to calculate the depth of irrigation water applied.

\textbf{3.5.5 Runoff}

The occurrence of any runoff prior to the ditch banks being put up was noted. Water that was still ponded on the plots 24 hours after irrigation had ceased was drained and the amount of runoff estimated from the area and the depth of water drained.

\textbf{3.5.6 Watertable depth}

Piezometers were installed in May 1998 to a depth of 3 metres in each corner of Site 1a. These were 45 mm internal diameter PVC pipe, with the bottom 1 metre slotted with 1 mm by 30 mm slots on two sides of the pipe every 10 mm. Coarse, washed sand was used to back-fill a 70 mm auger hole to the depth of the slotted screen. Dry Bentonite filling on top of this prevented the incursion of water down the sides of the test-well. Water-table depths in Site 1a were first read on 2\textsuperscript{nd} June 1998 and then every 2-3 days, after a rainfall event, and before and after an irrigation event. Water-table depths were measured from the top of each test-well and all readings were corrected back to a reference level (i.e. the average level of the soil surface in the surrounding plots).

Two test wells were installed to a depth of 3 m on 19\textsuperscript{th} March 1999 in the check-bank on the south side of the experimental area in Site 2.
3.6 Calculation of crop water use and crop factors

The hydrological data collected using the procedures above were used to calculate crop water use according to the following water balance equation:

\[
ET_c = (P + I_a + CR) - (\Delta S + RO + DP)
\]

Equation 3-6

where \(ET_c\) is crop evapotranspiration; \(P\) is rainfall; \(I_a\) is the gross applied depth of irrigation water; \(CR\) is capillary rise; \(\Delta S\) is the change in profile soil water content; \(RO\) is runoff; and \(DP\) is deep percolation. All components are expressed in mm equivalent depths and were summed to provide crop water use in the top 1.0 m of the soil profile. Whilst it is highly unlikely that all \(P\) contributed to \(\Delta S\), it was assumed that all \(P\) was effective in contributing to \(ET_c\).

Anderson (1980) calculated losses (\(L\)) of water from a crop system as:

\[
L = (P + S_t) - S_{\text{max}}
\]

Equation 3-7

where \(S_t\) is profile water content prior to a rainfall event at time \(t\) and \(S_{\text{max}}\) is the upper limit of available soil water. \(S_{\text{max}}\) was taken as the maximum observed profile water content to 1.0 m, which was 360 mm in the canola and 362 in the wheat at Site 1a in 1998. This equation makes no distinction between losses due to \(RO\) and those due to \(DP\). Although some individual plots had to be drained following rainfall on the 21\(^{st}\) to 23\(^{rd}\) June, run-off from the site was essentially zero in the winter period in 1998 so \(L\) is equivalent to \(DP\). However, not all rainfall is effective in recharging soil moisture and contributing to \(DP\) (as opposed to contributing to \(ET_c\)), so \(DP\) was calculated from Equation 3-7 using effective rainfall (\(P_e\)) rather than \(P\). \(P_e\) was estimated from

\[
P_e = P - ET_o \quad \text{for LAI} < 1
\]

\[
P_e = P - \text{LAI} \times S_c \quad \text{for LAI} \geq 1
\]

Equation 3-8

where \(P_e \geq 0\) and \(S_c\) is the canopy storage coefficient, which was determined by Leuning et al. (1994) for wheat at Wagga to be, on average, 0.55 mm.

Crop factors (\(K_c\)) were determined for consecutive 7 to 10 day periods according to

\[
K_c = \frac{ET_c}{ET_o}
\]

Equation 3-9

where \(ET_o\) was determined from class A pan data and the pan coefficient.
3.7 Deep percolation and capillary rise

DP and CR were obtained at Site 1a in 1998 from calculations of water fluxes across a plane at 100 cm using Darcy’s Law. Because the tensiometers were not installed until the 19th August, two other methods (i.e. water balance, described in Section 3.6, and analysis of water-table responses, described below) were used to calculate DP for the winter period. Both these approaches presumed that the waterlogged conditions during the winter period in 1998 ensured only downward fluxes.

Darcian flux calculations

Fluxes of water between 80 and 120 cm were calculated using the unit gradient method based on Darcy’s Law for unsaturated soil water flow (Bond 1998)

\[ q = -K(\theta) \left( \frac{d \psi_m(\theta)}{d z} + 1 \right) \]  

Equation 3-10

where \( K(\theta) \) and \( \psi_m(\theta) \) are the unsaturated hydraulic conductivity (cm day\(^{-1}\)) and the matric potential (cm) at the soil water content, \( \theta \), and \( q \) is the water flow per unit cross-sectional area per unit time (cm day\(^{-1}\)); positive downwards.

Paired NMM and tensiometer readings at 80 and 100 cm were used to derive the soil moisture characteristic and, using NMM measurements of \( \theta_v \) at 100 cm, \( K(\theta) \) was estimated using an equation described by Campbell (1985)

\[ K(\theta) = K_{fs} \times \left( \frac{\theta}{\theta_{fs}} \right)^{2b+3} \]  

Equation 3-11

where \( K_{fs} \) is the field saturated hydraulic conductivity, \( \theta_{fs} \) is the soil water content at field saturation and \( b \) is minus the slope of a straight line approximating the soil moisture characteristic on a log-log plot. Hume (1991) determined \( K_{fs} \) for the soil strata in the 75 to 100 cm range at Site 1 to be 1.42 cm day\(^{-1}\). \( \theta_{fs} \) was taken to be equal to the wettest observed moisture content at 100 cm depth, which was 0.37 cm cm\(^{-1}\). \( b \) for the 100 cm depth was determined to be -20.46 (\( P < 0.001, R^2 = 0.66, \) s.e. of obs = 0.172).

The hydraulic gradient \( (d\psi_m(\theta)/dz) \) was determined from \( \psi_m \) measurements at 80 and 120 cm and \( K(\theta) \) from \( \theta_v \) measurements at 100 cm. These were used in Equation 3-9 to
determine instantaneous fluxes at the 100 cm depth for each time \((t)\) that measurements were made. The mean flow rate \((\bar{q})\) operating during the time between two sets of NMM and tensiometer readings was assumed to be the simple arithmetic mean of the instantaneous rates at the beginning \((t_1)\) and end \((t_2)\) of that period. Cumulative flow \((Q)\) between 80 and 120 cm during this time was the product of \(\bar{q}\) and the time \((t_2 - t_1)\).

**Watertable response**

A number of rainfall events during the winter/spring period in 1998 were analysed using methods described by Armstrong & Narayan (1998) to determine the rise in water level due to the amount of rainfall that caused the response. The slope of the line of best fit from a composite plot of watertable level change \((\Delta h)\) on event rainfall provided a measure of the specific yield \((S_y)\) of the zone in which the water level was fluctuating. Recharge \((DP)\) was calculated from

\[
DP = \Delta h \times S_y
\]

**Equation 3-12**

### 3.8 Statistical analysis

The experimental designs were balanced and could have been analysed using analysis of variance (ANOVA). However, they were designed so that the treatment effects and variance components in a linear mixed spatial model could be analysed using residual maximum likelihood (REML). REML has the advantage over ANOVA of being able to account for spatial correlation (i.e. the soil in adjacent plots is more similar than soil in more distant plots). As well as blocking (based on the EM38 data), this was used to reduce the effect of soil variability on the statistical comparisons between treatments.

Following procedures described by Webster & Payne (2002), repeated measures analysis of variance was used to assess the significance of the treatment effects on the time series data (i.e. \(\theta_v\), \(S\), \(H\) and \(\Delta H/\Delta z\)) collected over the winter and spring periods.

Procedures in the statistical software program GENSTAT (Lawes Agricultural Trust, 2002) were used to analyse the experimental results.

A 5% level of significance was used to assess differences between treatments and ± values are quoted as one standard error (s.e.) of the mean unless otherwise indicated.
Chapter 4. Results

4.1 Weather data

The weather during the study period was close to long term average (Figure 4-1), though there were intra-seasonal differences in the occurrence of cooler and wetter periods.

Figure 4-1. Observed weekly rainfall (bars), pan evaporation (••••), weekly mean maximum (▲) and minimum (▼) temperatures for the 1998 (graphs a & c) and 1999 (graphs b & d) growing seasons. Solid lines show long term weekly mean evaporation (graphs a & b) and long term mean maximum and minimum temperatures (graphs c & d) at Deniliquin (source Clewett et al. 1999).
4.1.1 1998

Rainfall was average in June and greater than average in July, and temperatures were cooler than average in both months. This followed the early winter irrigation on 2\textsuperscript{nd} June and produced conditions that were not favourable for crop growth. Frosts on the 9\textsuperscript{th} to 11\textsuperscript{th} and 17\textsuperscript{th} to 20\textsuperscript{th} June (temperatures in the latter period down to -4\textdegree C) were followed by 24 mm of rain on the 21\textsuperscript{st} to 23\textsuperscript{rd} June. These cold, wet conditions particularly affected the canola, with chlorosis and ‘purpling’ of leaves observed at this time. These conditions persisted in July, with eight consecutive frosts between the 10\textsuperscript{th} to 17\textsuperscript{th} July followed by 33 mm of rain over the next 12 days. Water was observed to be lying on the surface of the plots on the 27\textsuperscript{th} July.

August was drier than average but, as in June and July, evaporation was lower than average. The rest of the season was close to average apart from two exceptional rain events: 42 mm over three days from the 21\textsuperscript{st} September and 58 mm on the 11\textsuperscript{th} November.

There were no severe frosts (screen temperature < 0\textdegree C) in September or October when the crops were flowering. Four days in October had temperatures > 30\textdegree C.

4.1.2 1999

Early May was dry and this delayed sowing until after 12 mm of rain on the 23\textsuperscript{rd} and 24\textsuperscript{th}. A further 12 mm fell two days after sowing (29-30 May) and provided good conditions for germination. Conditions following this varied, with average rainfall in June and August whilst July and September were very dry. Spring (Oct-Nov) was very much wetter than average and the rain was exceptionally well timed with regard to meeting crop water requirements (3\textsuperscript{rd} Oct = 24 mm; 10\textsuperscript{th} Oct = 25 mm; 23-24 Oct = 30 mm; 5\textsuperscript{th} Nov = 18 mm; 21\textsuperscript{st} Nov = 16 mm).

Nine frosts occurred in the last week of July and first week of August. Temperatures were hotter than average in September and cooler than average in October and November. There was frost (<0\textdegree C) on the 11\textsuperscript{th} and 12\textsuperscript{th} September when the canola was flowering and there was one day (9\textsuperscript{th} Oct) when temperatures exceeded 30\textdegree C.
4.2 Crop development

The canola flowered earlier and for longer than the wheat, being at mid-flowering in the second week of September when the wheat was at ear emergence and had finished flowering in the first week of October when wheat flowering was starting (Figure 4-2). The ripening and grain filling period in the (indeterminate) canola was approximately two weeks longer than that of the (determinate) wheat. Within irrigation treatments, the canola matured approximately a week earlier than the wheat in both years.

![Crop development diagram](image)

Figure 4-2. The duration of the growing period and some crop development stages in the canola and wheat in 1998 and 1999. Symbols are: ● sowing; ◊ buds visible (SM3.3) in canola and first node (DC30) in wheat; ▼ mid-flowering (SM4.5 and DC65); □ end flowering (SM4.9) in canola and ear emergence (DC50) in wheat; ▲ physiological maturity (PM) in C₀ and W₀; △ PM in C_{Full} and W_{Full}.

Irrigation extended the growing season of both crops (Figure 4-2), though this effect was not as great in wheat as it was in canola. Physiological maturity (PM) in C₀ occurred 13 and 17 days earlier than in C_{Full} in 1998 and 1999 respectively, which was equivalent to a difference of 230°Cd in 1998 and 284°Cd (>0°C) in 1999. Maturity of C₁ was intermediate between C₀ and C_{Full}, whereas C_{Def} matured with C_{Full} in 1998 and with C₁ in 1999. In contrast, W₁, W_{Def} and W_{Full} reached PM at similar times in both years and W₀ matured 9 and 11 days (129 and 188°Cd >3°C) earlier in 1998 and 1999.

The later sowing in 1999 shortened the growing seasons of both crops in the fully irrigated treatment by the same amount (12 days), mainly through a decrease in the time from sowing to flowering (20 days and 18 days shorter in 1999 for the canola and wheat respectively). This was offset by a slightly longer time from flowering to PM in 1999 (by 8 and 6 days for C_{Full} and W_{Full} respectively).
4.3 *Plant numbers*

4.3.1 *Establishment*

Plant densities at establishment are shown in Table 4-1. In 1998, mean establishment percentages were approximately 30% in the canola and 70% in the wheat. The low canola establishment percentage resulted in a plant population that was at the lower end of the “ideal” range for irrigated crops (i.e. 50 to 75 plants m\(^{-2}\); Colton & Sykes 1992). The opposite was true for the wheat, which had 25% more plants than recommended for irrigated crops (i.e. 150-200 plants m\(^{-2}\); Varley, *et al.* 1999).

In 1999, there was no significant difference (5% level) between the two Sites in the number of wheat or canola plants that established (Table 4-1). The establishment percent for the canola (65-70%) was better in 1999 than in 1998, but worse for the wheat (50%). This resulted in a canola plant density in 1999 that was both higher than expected and greater than the recommended 50-75 plants m\(^{-2}\). Wheat plant density was within the recommended 150-200 plants m\(^{-2}\) range.

<table>
<thead>
<tr>
<th></th>
<th>1998 Site 1a</th>
<th>1998 Site 2</th>
<th>1998 Site 1b</th>
<th>1999 Site 1a</th>
<th>1999 Site 2</th>
<th>1999 Site 1b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canola</td>
<td>54(\pm7)</td>
<td>120(\pm11)</td>
<td>109(\pm15)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>251(\pm5)</td>
<td>151(\pm14)</td>
<td>179(\pm12)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.2 *Physiological maturity*

Spring irrigation did not significantly affect canola plant numbers at PM in either 1998 or 1999 (Table 4-2). The wheat, on the other hand, did respond to spring irrigation. Spike density was consistently higher in the spring irrigated plots in both years and the difference between the \(W_0\) and \(W_{Full}\) plots was significant (Table 4-2). The \(W_1\) plots also had consistently higher spike numbers than the \(W_{Def}\) plots, though this difference was only significant in 1998.
Table 4-2. Mean plant density of the canola (stems m⁻²) and wheat (spikes m⁻²) crops at physiological maturity in 1998 and 1999. Different superscripts indicate a significant difference at the 5% level for the same crop. Values in parentheses are the s.e. mean (n = 4).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1998</th>
<th>1999</th>
<th>1999</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Site 1a</td>
<td>Site 2</td>
<td>Site 1b</td>
</tr>
<tr>
<td>C₀</td>
<td>50ᵃ</td>
<td>83ᵃ</td>
<td></td>
</tr>
<tr>
<td>C₁</td>
<td>47ᵃ</td>
<td>95ᵃ</td>
<td></td>
</tr>
<tr>
<td>C_{Def}</td>
<td>51ᵃ</td>
<td>80ᵃ</td>
<td></td>
</tr>
<tr>
<td>C_{Full}</td>
<td>53ᵃ</td>
<td>88ᵃ</td>
<td>47 (6.9)</td>
</tr>
<tr>
<td>W₀</td>
<td>504ᵃ</td>
<td>500ᵃ</td>
<td></td>
</tr>
<tr>
<td>W₁</td>
<td>552ᵇ</td>
<td>530ᵇ</td>
<td></td>
</tr>
<tr>
<td>W_{Def}</td>
<td>507ᵃ</td>
<td>522ᵇ</td>
<td></td>
</tr>
<tr>
<td>W_{Full}</td>
<td>553ᵇ</td>
<td>573ᵇ</td>
<td>562 (23.6)</td>
</tr>
</tbody>
</table>

Significance of differences between means: ns – not significant; *** (P < 0.001)

4.3.3 Changes in canola stem density over the growing season

In 1998, growth of low stem branches and later emerging seedlings increased the number of canola stems counted during the vegetative phase of development. Stem density then remained constant from buds visible (SM3.3) until the end of flowering, after which some of the weaker stems and smaller plants died. This loss was roughly equal to the gain early in the season so there was no significant difference in stem density between establishment and PM (Figure 4-3).

In 1999, establishment was higher than in 1998 and stem density did not increase during the vegetative phase. In Site 2, stem density decreased between buds visible and mid-flowering. In Site 1b, stem density stayed high until mid-flowering. After mid-flowering, stem numbers in Site 2 remained constant whereas stem numbers in Site 1b declined steadily for the rest of the growing season (Figure 4-3). There were significantly (P<0.01) less plants at PM in both Sites than there were at establishment. This decrease was roughly 30% in Site 2 and 60% in Site 1b. One consequence of this was that the final plant density at PM in Site 1b in 1999 was similar to that in Site 1a in 1998 (Table 4-2).
### 4.3.4 Changes in wheat spike density over the growing season

Both the number of plants at establishment and the maximum spike density were greater in 1998. The pattern of change however was similar across both years, with spike density peaking at a similar thermal time around the end of tillering (i.e. 530 and 540°Cd >3°C in 1998 and 1999 respectively) and then decreasing to approximately 550 spikes m\(^{-2}\) at flowering (Figure 4-4). Spike numbers then either declined slightly (if unirrigated) or remained constant (if irrigated) until PM.
4.4 Green leaf area

The fully irrigated crops (i.e. W\text{Full} & C\text{Full}) in Site 1a had a consistently higher green leaf area (GLA) than the unirrigated crops (i.e. W\text{0} & C\text{0}) after the first spring irrigation in 1998. These differences, however, were not significant. Biomass samples were collected more regularly in 1999 but irrigation effects on GLA were not assessed as GLA was only measured on the samples taken from the crops in Site 1b.

4.4.1 Canola

The maximum GLA in the canola in Site 1 was 5.7 ± 0.4 in 1998 and 3.7 ± 0.4 in 1999. A similar pattern of growth is apparent in both years when GLA is plotted against date (Figure 4-5), but not when GLA is plotted on accumulated thermal time (>0°C). Peak GLA coincided with flowering in early September in both years. From Figure 4-5, the canola attained a GLA of 1 on approximately the 30\textsuperscript{th} July in 1998 and the 10\textsuperscript{th} August in 1999 (89 and 70 DAS or 829 and 599°Cd (>0°C) respectively) and full ground cover (GLA >3) was reached on the 21\textsuperscript{st} August in 1998 and the 24\textsuperscript{th} August in 1999 (111 and 84 DAS or 1048 and 728°Cd (>0°C) respectively).

It was observed that plants in the C\text{Full} treatment retained green leaf longer than the C\text{0} treatment in both years.

![Figure 4-5](image_url)

Figure 4-5. Mean green leaf area index of the canola (C\text{Full}) in Site 1 in 1998 and 1999 plotted against (a) calendar time and (b) accumulated thermal time >0°C since sowing. Error bars show the standard error of the mean (n=3 in 1998 and n = 4 in 1999).
4.4.2 Wheat

GLA in the wheat peaked at ear emergence (DC50; mid-September) at 4.5 ± 0.4 in 1998 and 4.5 ± 0.1 in 1999. Unlike the canola, the pattern of growth in leaf area in the wheat was similar across years when GLA was plotted on thermal time (>3°C) but not when plotted against calendar time (Figure 4-6). From Figure 4-6, the wheat attained a GLA of 1 on approximately the 16th June in 1998 and the 10th August in 1999 (45 and 70 DAS or 380 and 389°Cd (>3°C) respectively) and full ground cover (GLA ≥ 3) occurred on the 3rd August in 1998 and the 28th August in 1999 (93 and 88 DAS or 586 and 518°Cd (>3°C) in 1998 and 1999 respectively).

Disease (Septoria) caused premature leaf senescence in the W$_{Full}$ plots in 1998. It was observed that green leaf was retained longer in the W$_{Full}$ treatment than in the W$_{0}$ treatment in 1999.

Figure 4-6. Mean green leaf area index of the wheat (W$_{Full}$) in Site 1 in 1998 and 1999 plotted against (a) calendar time and (b) accumulated thermal time >3°C since sowing. Error bars show the s.e. of the mean (n=3 in 1998 and n = 4 in 1999).

4.5 Shoot biomass

As expected, there was no significant irrigation treatment effect on the amount of above ground biomass prior to the first spring irrigation in either 1998 or 1999. The exception was the C$_{Def}$ treatment in 1998, which had significantly less biomass than the other canola plots on the 14th August (Table 4-3) because early crop growth was affected by waterlogging in plot 2-5 and pests in plot 1-8. Reanalysis of the data using a pseudo-
variate as a covariate (Dyke and Pearce 2000) confirmed plots 1-8 and 2-5 as being significantly different and showed there was no significant treatment effect on 14th August 1998 when this difference was accounted for (P = 0.5% as assessed by the change in deviance from model 1 to 2; within block variance was reduced from 2357 to 2271).

Plot 1-6 also had an unusually low biomass at PM in 1998 and it was suspected that 5 crop rows rather than 6 had been harvested. The method of (Dyke & Pearce 2000) showed that plot 1-6 was significantly different to the rest of the data set (P < 0.5% as assessed by the change in deviance from model 1 to 2; within block variance was reduced from 10,076 to 8,136). Rather than treating plot 1-6 as missing, its biomass was estimated from its grain yield and harvest index and this value was used in the analysis presented in Table 4-3.

Spring irrigation had no significant affect on above ground biomass at PM in either crop in 1998 or in the canola in 1999. It did significantly increase crop growth in the wheat in 1999, with the W1 and WFull plots having significantly more above ground biomass than the W0 plots (Table 4-4). Although not significant, in both years and for both crops, the single irrigation treatments had at least as much biomass at PM as the deficit irrigated treatments, if not more.

The crop growth curves showed a similar pattern across years when shoot biomass was plotted against Julian date for the canola (Figure 4-7) and when plotted against accumulated thermal time (>3°C) from sowing for the wheat (Figure 4-8). In the canola, a period of rapid growth began at the start of August and finished at the start of October when flowering finished (SM4.9) in both 1998 and 1999. The period of rapid growth in the wheat began approximately 400°Cd (>3°C) after sowing and finished approximately 600°Cd (>3°C) later when the crops started flowering (DC61). The biomass of the canola in Site 1a (1998) and Site 2 (1999) at the end of flowering was similar (Table 4-3 & Table 4-4), but the biomass of the canola in Site 1b in 1999 was considerably lower (Figure 4-7). All three wheat crops had a similar dry shoot biomass at DC61 (i.e. approximately 1000°Cdays >3°C after sowing in Figure 4-8).
Table 4-3. Treatment mean above ground dry biomass (n=3) from quadrat cuts in the wheat and canola in Site 1a in 1998. Different superscripts indicate significant differences at the 5%.

<table>
<thead>
<tr>
<th>Date of Harvest</th>
<th>Dry Weight (g m⁻²)</th>
<th>Canola mean</th>
<th>Wheat mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>14th Aug</td>
<td>175 a</td>
<td>143</td>
<td>342</td>
</tr>
<tr>
<td>11th Sept</td>
<td>760 a</td>
<td>718</td>
<td>736</td>
</tr>
<tr>
<td>29th Sept</td>
<td>747 a</td>
<td>722</td>
<td>933</td>
</tr>
<tr>
<td>various</td>
<td>991 a</td>
<td>993</td>
<td>1302</td>
</tr>
</tbody>
</table>

Stage – canola: SM3.3, SM4.5, SM4.9
– wheat: DC31, DC50, DC61
Quadrat area: 0.72 m², 0.36 m², 1.08 m²

Physiological Maturity.

Table 4-4. Predicted mean above ground dry biomass (n=4) from quadrat cuts in the wheat and canola in Site 2 in 1999. Different superscripts indicate significant difference at the 5% level.

<table>
<thead>
<tr>
<th>Date of Harvest</th>
<th>Dry Weight (g m⁻²)</th>
<th>Canola mean</th>
<th>Wheat mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th Oct</td>
<td>665 a</td>
<td>731</td>
<td>905</td>
</tr>
<tr>
<td>various</td>
<td>951 a</td>
<td>1038</td>
<td>1608</td>
</tr>
</tbody>
</table>

Stage – canola: SM4.9
– wheat: DC61
Quadrat Area: 1.08 m²

Physiological Maturity.

Significance of differences between means: ns – not significant; * (P < 0.05); ** (P < 0.01); *** (P < 0.001)
Figure 4-7. Dry shoot biomass of the canola crops in 1998 and 1999 plotted against calendar time. Error bars show the s.e. of the mean (n=3 in 1998 and n = 4 in 1999).

Figure 4-8. Dry shoot biomass of the wheat crops in 1998 and 1999 plotted against accumulated thermal time (>3°C) since sowing. Error bars show the s.e. of the mean (n=3 in 1998 and n = 4 in 1999).
### 4.6 Grain yield

Both crop type and irrigation intensity had highly significant effects on grain yield in 1998 and 1999 (Table 4-5). Wheat yields were significantly higher than canola yields, with the ratio of canola to wheat yield being 0.56 in 1998 and 0.50 in 1999. Increasing the irrigation intensity significantly increased grain yields in both 1998 and 1999, with the yields of the fully irrigated treatment significantly greater than that of I\(_0\) for both the canola and the wheat. The yield difference between I\(_0\) and I\(_{\text{Full}}\) was very similar in both years, being 0.35 and 0.34 t ha\(^{-1}\) for the canola and 1.20 and 1.14 t ha\(^{-1}\) for the wheat in 1998 and 1999 respectively.

Table 4-5. REML analysis of grain yields from Site 1a in 1998 and Site 2 in 1999. Yields are reported at standard moisture contents (canola at 8.5%; wheat at 12%). Different superscripts indicate significant difference at the 5% level. Values in parantheses are the SE of the mean (n=4).

<table>
<thead>
<tr>
<th>Grain Yield (t ha(^{-1}))</th>
<th>Year - Site</th>
<th>1998 – Site 1a</th>
<th>1999 – Site 2</th>
<th>1999 – Site 1b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canola Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(_0)</td>
<td>2.89(^a)</td>
<td>3.02(^a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(_1)</td>
<td>2.90(^a)</td>
<td>3.62(^b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(_{\text{Def}})</td>
<td>3.02(^{ab})</td>
<td>3.44(^b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(_{\text{Full}})</td>
<td>3.24(^b)</td>
<td>3.36(^b)</td>
<td>2.74((0.10))</td>
<td></td>
</tr>
<tr>
<td>Wheat Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W(_0)</td>
<td>4.77(^c)</td>
<td>6.16(^c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W(_1)</td>
<td>4.86(^c)</td>
<td>6.59(^d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W(_{\text{Def}})</td>
<td>5.78(^d)</td>
<td>6.68(^d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W(_{\text{Full}})</td>
<td>5.97(^d)</td>
<td>7.30(^e)</td>
<td>6.72((0.13))</td>
<td></td>
</tr>
<tr>
<td>Wheat Mean</td>
<td>5.34</td>
<td>6.68</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Significance of differences between means: ns – not significant; * (P < 0.05); ** (P < 0.01); *** (P < 0.001)

Early season growth of the canola in plots 1-8 and 2-5 in Site 1a in 1998 was affected by waterlogging and pests. However, the final grain yield of these plots was not significantly affected so they were included in the REML analysis. Plots B-5 and B-6 at Site 2 suffered herbicide (Tigrex™) damage in 1999 after being sprayed on the 19\(^{th}\) August. Enough crop remained unaffected for representative biomass samples to be cut, but grain yields from the plot harvester were low and the yields of the two plots contributed significantly (P<0.001) to within-block variance. Because the cause was known and not an artefact of the experimental design, the yields from plots B-5 and B-6 were set as missing values in the analysis of the Site 2 yield data.
The single spring irrigation had the same effect on both crops, significantly increasing yields in 1999 but not in 1998. By comparison, I_{Def} had a similar effect to I_{full} and increased yields in both years when compared to I_0. This increase was significant in 1998 and 1999 for the wheat, but only significant in 1999 for the canola. In only one instance, the wheat in 1998, was the yield of I_{Def} significantly greater than that of I_1 and, in fact, the trend in the canola in 1999 was for lower yield if more than one irrigation was applied. Only in the wheat in 1999 did I_{Full} yield significantly more than I_{Def}.

### 4.7 Yield components

#### 4.7.1 Grains per spike and pods per plant

There was no significant effect of irrigation intensity on the number of grains per spike in the wheat in either 1998 or 1999. The average number of grains per spike was 34 ± 1.5 in 1998 and 33 ± 1.1 in 1999.

The average number of pods per plant in 1998 was 156 ± 9, with no significant effect of irrigation treatment. The number of pods per plant was not measured in 1999.

#### 4.7.2 Harvest index

The only significant effect of irrigation on harvest index (HI) occurred in the wheat in 1998 where HI increased from 0.33 in W_0 to 0.37 in W_{Full} (Table 4-6). Irrigation did not significantly affect the HI of the canola in either year 1998 or 1999. The HI of the canola, in fact, was remarkably constant and the average across irrigation treatments, years and sites was 0.34. The HI of the wheat, on the other hand, was considerably lower in 1998 (Site 1a) than it was in 1999 (both Site 2 and 1b).
Table 4-6. REML analysis of the harvest index (HI) data from Site 1a in 1998 and Site 2 in 1999. The mean HI of each treatment is shown, with superscripts indicating significant difference at the 5% level for the same crop. Values in parentheses are the standard error of the mean (n=4).

<table>
<thead>
<tr>
<th>Year - Site</th>
<th>Harvest Index</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1998 – Site 1a</td>
<td>1999 – Site 2</td>
<td>1999 – Site 1b</td>
</tr>
<tr>
<td>C₀</td>
<td>0.33</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>C₁</td>
<td>0.32</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>C_Def</td>
<td>0.34</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>C_Full</td>
<td>0.34</td>
<td>0.36</td>
<td>0.35 (0.007)</td>
</tr>
<tr>
<td></td>
<td>0.33</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.33</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.34</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.36</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.37</td>
<td>0.43</td>
<td>0.46 (0.003)</td>
</tr>
</tbody>
</table>

Crop Mean

W₀                  0.33
W₁                  0.34
W_Def               0.36
W_Full              0.37

Wheat Mean

0.35

Crop irrigation

0.014
0.016
0.030
0.030

Significance of differences between means: ns – not significant; * (P < 0.05); *** (P < 0.001)

4.7.3 Grain weight

The results of the REML analysis of the grain weight data is shown in Table 4-7, together with the estimated mean 1000 grain weight of each treatment. In 1998, there was a trend for increasing grain size with increasing irrigation intensity in both the canola and the wheat. The grain of the C₀ and C₁ plots was significantly lighter than that of the C_Def and C_Full treatments. The result in the wheat was similar, though the difference between the W₀ and W_Def treatments was not significant at the 5% level. In 1999, by contrast, irrigation intensity had no significant effect on grain size in either the wheat or the canola. Comparing grain weights across years and sites in the C_Full treatment, there was little difference between Site 1a in 1998 and Site 2 in 1999 whereas grain from Site 1b in 1999 was approximately 5% lighter. The same comparison in the W_Full treatment shows that grains from the wheat crops in Site 1 had similar weights in both 1998 and 1999, whereas grain from Site 2 was approximately 15% heavier.
Table 4-7. 1000 grain weight of the crops in Site 1a in 1998 and Sites 2 and 1b in 1999 at standard moisture contents (canola at 8.5%; wheat at 12%). The results of the REML analysis conducted on the transformed (i.e. normalised) data is shown. Values in square brackets are the normalised values and those in parantheses are the s.e. of the mean (n=4).

<table>
<thead>
<tr>
<th>Year - Site</th>
<th>1998 – Site 1a</th>
<th>1999 – Site 2</th>
<th>1999 – Site 1b</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&lt;sub&gt;0&lt;/sub&gt;</td>
<td>3.48 [-0.98]&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.00 [0.80]</td>
<td></td>
</tr>
<tr>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
<td>3.54 [-0.72]&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.94 [0.21]</td>
<td></td>
</tr>
<tr>
<td>C&lt;sub&gt;Def&lt;/sub&gt;</td>
<td>3.83 [0.63]&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.88 [-0.36]</td>
<td></td>
</tr>
<tr>
<td>C&lt;sub&gt;Full&lt;/sub&gt;</td>
<td>3.93 [1.07]&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.85 [-0.65]</td>
<td>3.69 (0.05)</td>
</tr>
</tbody>
</table>

Canola Mean: 3.69 3.91

| Wheat Mean | 30.1 | 38.5 |

Superscripts beside each mean indicate significant irrigation treatment effects (5% level).

The difference in grain size between the wheat and canola resulted in a very non-normal distribution of residuals when the REML analysis was conducted using the raw 1000 grain weight data. To overcome this, the data was transformed using the ‘standardise’ command in GENSTAT to normalise the grain weights within each crop type. Because the mean of the normalised values for each crop across all irrigation treatments is 0, this test only showed the significance of the irrigation treatment effects.

4.7.4 Grain quality

There was no significant effect of irrigation intensity on either canola grain oil content or wheat grain protein content and no appreciable differences between 1998 and 1999. Average canola seed oil content was 41.8% and average wheat grain protein content was 11.2% across years and irrigation treatments.
4.8 **Plant water potential**

The results of the measurements of leaf (wheat) and stem (canola) water potentials ($\psi_p$) in the crops in Site 1a during spring in 1998 are shown in Table 4-8 and Table 4-9. On the morning prior to the first irrigation (8\textsuperscript{th} September), $\psi_p$ in the two crops was not significantly different (Table 4-9). No rain fell in the week following this irrigation and by the 17\textsuperscript{th} September signs of water stress were observed at mid-day in the unirrigated treatment: the flag leaf of the wheat in the W\textsubscript{0} plots was rolled and plants were “blue and in the C\textsubscript{0} plots the lower leaves of the canola were wilted. Mid-day measurements confirmed these observations, with $\psi_p$ in the unirrigated crops being appreciably lower than in the irrigated crops (Table 4-8). This difference was significant in the wheat.

Forty five mm of rain fell over a three day period shortly after these initial measurements (21\textsuperscript{st} to 23\textsuperscript{rd} September), alleviating the water stress in the W\textsubscript{0} and C\textsubscript{0} plots. This was confirmed by measurements on the 30\textsuperscript{th} September that showed there was no significant difference in dawn $\psi_p$ between the irrigated and unirrigated crops (Table 4-8). Canola $\psi_p$ on the 30\textsuperscript{th} September was similar to that measured on the 8\textsuperscript{th} September prior to the first spring irrigation (i.e. $\approx -0.73$ MPa). Wheat $\psi_p$, however, had increased and was significantly greater than canola $\psi_p$ at this time (Table 4-8). Later measurements show that this inter-crop difference was significant and persisted for the rest of the season (Table 4-9).

Table 4-8. Average leaf (wheat) and stem (canola) water potentials (MPa) of the crops in Site 1a prior to 45 mm of rainfall on the 21\textsuperscript{st}, 22\textsuperscript{nd} and 23\textsuperscript{rd} September 1998 and then one week later.

<table>
<thead>
<tr>
<th></th>
<th>Pre Rain</th>
<th>Post Rain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18\textsuperscript{th} Sept, noon</td>
<td>30\textsuperscript{th} Sept, dawn</td>
</tr>
<tr>
<td>C\textsubscript{0}</td>
<td>-1.27 \textsuperscript{ab}</td>
<td>-0.75 \textsuperscript{a}</td>
</tr>
<tr>
<td>C\textsubscript{1}, Def, Full</td>
<td>-0.89 \textsuperscript{b}</td>
<td>-0.69 \textsuperscript{a}</td>
</tr>
<tr>
<td>W\textsubscript{0}</td>
<td>-1.84 \textsuperscript{a}</td>
<td>-0.31 \textsuperscript{b}</td>
</tr>
<tr>
<td>W\textsubscript{1}, Def, Full</td>
<td>-0.75 \textsuperscript{b}</td>
<td>-0.33 \textsuperscript{b}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ns</th>
<th>***</th>
</tr>
</thead>
<tbody>
<tr>
<td>crop</td>
<td></td>
<td>***</td>
</tr>
<tr>
<td>irrigation</td>
<td>*</td>
<td>ns</td>
</tr>
<tr>
<td>crop\times irrigation</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>sed for crop\times irrigation</td>
<td>0.32</td>
<td>0.03</td>
</tr>
<tr>
<td>5% lsd for crop\times irrigation</td>
<td>0.78</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Significance of differences between means: ns – not significant; * (P < 0.05); ** (P < 0.01); *** (P < 0.001)

Different superscripts indicate significant differences between means for the crop\times irrigation interaction.
Table 4-9. Average dawn leaf (wheat) and stem (canola) water potentials (MPa) of the crops from measurements made prior to four of the spring irrigations in Site 1a in 1998.

<table>
<thead>
<tr>
<th>Pre 1&lt;sup&gt;st&lt;/sup&gt; Irrigation</th>
<th>Pre 2&lt;sup&gt;nd&lt;/sup&gt; Irrigation of W&lt;sub&gt;Full&lt;/sub&gt; &amp; C&lt;sub&gt;Full&lt;/sub&gt;</th>
<th>Pre 2&lt;sup&gt;nd&lt;/sup&gt; Irrigation of W&lt;sub&gt;Def&lt;/sub&gt; &amp; C&lt;sub&gt;Def&lt;/sub&gt;</th>
<th>Pre 3&lt;sup&gt;rd&lt;/sup&gt; Irrigation of W&lt;sub&gt;Full&lt;/sub&gt; &amp; C&lt;sub&gt;Full&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8&lt;sup&gt;th&lt;/sup&gt; Sept, dawn</strong></td>
<td><strong>10&lt;sup&gt;th&lt;/sup&gt; Oct, dawn</strong></td>
<td><strong>15&lt;sup&gt;th&lt;/sup&gt; Oct, dawn</strong></td>
<td><strong>23&lt;sup&gt;rd&lt;/sup&gt; Oct, dawn</strong></td>
</tr>
<tr>
<td>all canola</td>
<td>-0.74</td>
<td>C&lt;sub&gt;0&lt;/sub&gt;</td>
<td>C&lt;sub&gt;0&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;1&lt;/sub&gt;, Def, Full</td>
<td>-1.08&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.91&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;1&lt;/sub&gt;, Def</td>
<td>-0.77&lt;sup&gt;ab&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;Full&lt;/sub&gt;</td>
<td>-0.53&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>-0.46&lt;sup&gt;cd&lt;/sup&gt;</td>
</tr>
<tr>
<td>all wheat</td>
<td>-0.67</td>
<td>W&lt;sub&gt;0&lt;/sub&gt;</td>
<td>W&lt;sub&gt;0&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>W&lt;sub&gt;1&lt;/sub&gt;, Def, Full</td>
<td>-0.75&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>-0.51&lt;sup&gt;cd&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>W&lt;sub&gt;Full&lt;/sub&gt;</td>
<td>-0.51&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>-0.66&lt;sup&gt;bc&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>-0.23&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-0.23&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-0.42&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

| crop                          | ns                                             | **crop**                                      | **crop**                                      | **crop**                                      |
| sed                           | 0.06                                          | 0.01                                          | 0.16                                          | 0.34                                          |
| lsd (5%)                      | 0.16                                          | 0.04                                          | 0.04                                          | 0.22                                          |
| cropxirrigation               | ns                                            | ns                                            | ns                                            | ns                                            |
| sed                           | 0.15                                          | 0.15                                          | 0.15                                          | 0.10                                          |
| lsd (5%)                      | 0.34                                          | 0.34                                          | 0.34                                          | 0.22                                          |

Significance of differences between means: ns – not significant; * (P < 0.05); ** (P < 0.01); *** (P < 0.001)
Different superscripts indicate significant differences between means for the cropxirrigation interaction

There was 3.8 mm of rain on the 2<sup>nd</sup> and 10.4 mm on the 6<sup>th</sup> October. While this increased $\psi_p$ in the canola $\psi_p$, there was still a significant difference between the two crops prior to the second irrigation of I<sub>Full</sub> on the 10<sup>th</sup> October (Table 4-9). Five days later, on the 15<sup>th</sup> October, significant irrigation treatment effects had appeared. There was a consistent trend in both crops, with the treatments receiving the least amount of water having the lowest $\psi_p$ (i.e. I<sub>Full</sub> > I<sub>Def</sub> and I<sub>1</sub> > I<sub>0</sub>). $\psi_p$ in I<sub>Full</sub> did not change significantly between the 10<sup>th</sup> and 15<sup>th</sup> October (the wheat may have increased slightly), but $\psi_p$ in the other irrigation treatments had decreased and the difference between I<sub>Full</sub> and I<sub>0</sub> in both crops had become significant.

By the time of the third irrigation of I<sub>Full</sub> on the 23<sup>rd</sup> October, $\psi_p$ in I<sub>0</sub> and I<sub>1</sub> were similar, though $\psi_p$ in the canola was still lower than in the corresponding irrigation treatment in the wheat (the difference between C<sub>0</sub> and W<sub>0</sub> was significant). $\psi_p$ in the C<sub>Full</sub> and W<sub>Full</sub> treatments, however, had converged and there was no significant difference between these two treatments. $\psi_p$ of the crops in I<sub>Full</sub> was significantly higher than that of the crops in I<sub>0</sub> and I<sub>1</sub>. I<sub>Def</sub> was not measured at this time.
4.9 Soil water content

4.9.1 Winter 1998

Figure 4-9 shows there was little apparent difference in volumetric water content ($\theta_v$) under the wheat and the canola during the winter period in 1998. This was confirmed by repeated measures analysis of variance (ANOVA) which showed that $\theta_v$ under the two crops were not significantly different (5% level) at any depth of reading during the period 29th May to 5th August. This analysis also showed that $\theta_v$ at the 120 cm depth was essentially constant throughout this period.

![Figure 4-9. Mean volumetric water content (m$^{-1}$) at nine depths under the wheat (---) and the canola (—) in Site 1a between 29th May and the 5th August 1998. Error bars show the l.s.d. (5% level) and the horizontal line (····) indicates the water content when air-filled porosity is 0.1 m$^{-1}$.](image-url)
An air-filled porosity of 0.10 cm cm$^{-1}$ is considered the “critical limit” for root growth (Grable & Siemer 1968) and this limit has been confirmed for heavy clay soils in Australia (McKenzie & McBratney 2001). This limit was estimated for each depth from bulk and particle density data and is shown as the horizontal dotted line in Figure 4-9.

Ante-dependence analysis in GENSTAT was used to determine whether an apparent difference (Figure 4-9) between the two crops in the rate of change in $\theta_v$ in the topsoil was significant. Only the 10 cm depth was analysed as the surface horizon was sampled gravimetrically prior to the 18$^{th}$ July and the record was not contiguous. The analysis (not presented) showed a first order ante-dependence structure and confirmed the ANOVA result of no significant overall effect of crop type on $\theta_v$ at 10 cm during the winter period. However, $\theta_v$ at 10 cm did decline significantly more under the canola than under the wheat between the 12$^{th}$ and 14$^{th}$ July. There were a number of other occasions when $\theta_v$ at 10 cm also declined appreciably more under the canola than under the wheat (i.e. 13$^{th}$ to 18$^{th}$ June, 29$^{th}$ June to 1$^{st}$ July, 9$^{th}$ to 12$^{th}$ July and 30$^{th}$ July to 1$^{st}$ August), though these differences were only significant at the 10% level.

**4.9.2 Spring 1998**

Differences in $\theta_v$ between the wheat and the canola appeared in spring as evaporation rates increased (Figure 4-1). These crop-type differences were assessed for each depth and irrigation treatment using repeated measures ANOVA. The changes in $\theta_v$ at each depth in each irrigation treatment during the spring period are shown in Figure 4-10, Figure 4-11, Figure 4-12, and Figure 4-13 and significant differences (5% level) in $\theta_v$ between the two crops are indicated.

With the onset of warmer weather in spring, the surface horizon (0-5 cm) in all irrigation treatments dried more under the wheat than it did under the canola. By the time of the first spring irrigation (8$^{th}$ Sept), the difference in surface soil $\theta_v$ between the crops had become significant. This situation persisted for the rest of the season in I$_0$ (Figure 4-10). In the irrigated treatments, the surface soil under the wheat was significantly drier between the 16$^{th}$ and 19$^{th}$ September and again on the 28$^{th}$ September. This did not persist and only recurred for a short period in mid-October in I$_{Def}$ (Figure 4-12).
Figure 4-10. Mean volumetric water content (m $m^{-1}$) at nine depths under the wheat (---) and the canola (—) in I₀ in Site 1a between 5th Aug and 13th Nov 1998. Significant differences (5% level) in $\theta$ between the wheat and the canola at a particular depth and time are indicated (+). Error bars show the least significant differences of the means (5% level).
Figure 4-11. Mean volumetric water content (m m$^{-3}$) at nine depths under the wheat (---) and the canola (―) in Site 1a between 5th Aug and 13th Nov 1998. Significant differences (5% level) in $\theta_v$ between the wheat and the canola at a particular depth and time are indicated (•). Error bars show the least significant differences of the means (5% level).
Figure 4-12. Mean volumetric water content (m m$^{-1}$) at nine depths under the wheat (---) and the canola (―) in Site 1a between 5th Aug and 13th Nov 1998. Significant differences (5% level) in $\theta_v$ between the wheat and the canola at a particular depth and time are indicated (•). Error bars show the least significant differences of the means (5% level).
Figure 4.13. Mean volumetric water content (m m$^{-1}$) at nine depths under the wheat (---) and the canola (—) in $I_{f}$ in Site 1a between 5th Aug and 13th Nov 1998. Significant differences (5% level) in $\theta_v$ between the wheat and the canola at a particular depth and time are indicated (*). Error bars show the least significant differences of the means (5% level).
There was no significant difference between $\theta_v$ under the two crops in the Full irrigation treatment at any depth other than the surface horizon. There was a trend for $W_{\text{Full}}$ to be drier at 20 and 30 cm and $C_{\text{Full}}$ to be drier at 60 and 80 cm (Figure 4-13). These trends were also present in the Deficit and 1 irrigation treatments and they became significant in the sub-soil as the season progressed. $C_{\text{Def}}$ was significantly drier than $W_{\text{Def}}$ at 80 cm from the 29th October (Figure 4-12) and $C_1$ was significantly drier than $W_1$, firstly at 60 cm from the 29th October and then at 80 cm from 4th November (Figure 4-11).

The same trends observed in the irrigated treatments were also present in the unirrigated treatments. However, differences in the sub-soil were not as great (as in the 1 and Deficit irrigation treatments) whilst the differences in the B horizon were greater. $C_0$ only became significantly drier than at $W_0$ at 100 cm at the end of the season but $W_0$ became significantly drier than $C_0$ at 20 and 30 cm comparatively early in spring (Figure 4-10).

For all irrigation treatments, there was no significant effect of crop type on $\theta_v$ at 120 cm. Neither was there any significant effect of “time” on $\theta_v$ at this depth, indicating that $\theta_v$ did not change appreciably at 120 cm under either crop during the whole of the monitoring period, irrespective of the spring irrigation treatment. This was also the situation at 100 cm for the deficit and fully irrigated treatments.

It is of some note that despite the differences in the patterns of soil water extraction by the two crops described above, the profile water contents (0-1 m) under the wheat and the canola were not significantly different within each irrigation treatment at any time during the spring period.

4.9.3 1999

The highly variable nature of the sub-soil at Site 2 resulted in a lack of significance in the differences between $\theta_v$ under the two crops. Furthermore, the high October rainfall (Figure 4-1, page 56) negated any difference between the irrigation treatments. The crops did not appear to use much water below 40 cm and the patterns of soil water use seen in 1998 were not observed (Figure 4-14).
Figure 4-14. NMM count ratio ($C_R$) plotted against soil depth, showing the wettest and driest soil profiles observed in (a) C_{Full}, (b) W_{Full}, (c) C_0, and (d) W_0 treatments in Site 2 in spring 1999. Wettest profiles (--- ▲ ---) measured on 25th October and driest profiles (”×”) measured on 20th November. Error bars show ± se mean (n=4).
4.10 Soil water potential

Figure 4-15 shows the total hydraulic potential \( (H) \) at 80, 100 and 120 cm in \( I_0, I_1 \) and \( I_{\text{Full}} \) in Site 1a from the first reading on 19th August to the 14th November 1998\(^1\).

Between the 19th August and the first spring irrigation on the 8th September there was no significant difference between the crops or irrigation treatments at any depth of reading. The soil at these depths was relatively wet during this period and average matric potential \( (\psi_m) \) was -85.6, -70.2 and -49.5 cm of water at the 80, 100 and 120 cm depths respectively. This corresponded to an average \( H \) for the period of -164.4, -169.9 and -169.0 cm of water at the 80, 100 and 120 cm depths respectively, indicating the existence of a zero flux plane at an approximate depth of 100 cm. There was a slight but consistent decrease in \( H \) at all depths under both crops at the end of this period (i.e. in the first week of September), but this change was not significant.

Repeated measures ANOVA showed there was a significant time \( \times \) crop \( \times \) irrigation interaction effect on \( H \) at all three depths following the first spring irrigation (Figure 4-15). \( H \) did not differ significantly between the two crops or change significantly over time at any depth in the fully irrigated treatment throughout the monitoring period. In \( I_0 \) and \( I_1 \), \( H \) declined significantly with time during the spring and this decline occurred at a faster rate under the canola compared to the wheat. By the end of the season, the soil at all three depths in \( I_0 \) and \( I_1 \) was significantly drier under the canola (Figure 4-15). This drying also began earlier under the canola, with significant differences between \( C_0 \) and \( C_{\text{Full}} \) and between \( C_1 \) and \( C_{\text{Full}} \) at 120 cm occurring after the 11th and 29th October respectively. \( W_0 \) and \( W_1 \), on the other hand, did not differ significantly from \( W_{\text{Full}} \) at 120 cm until the final reading on the 14th November.

The soil remained constantly and equally wet at depth under both the wheat and the canola in \( I_{\text{Full}} \). By contrast, the sub-soil under both crops was dried when only 0 or 1 irrigation was applied in spring. Furthermore, the soil was dried down earlier, to a greater extent and to a greater depth in \( I_0 \) compared to \( I_1 \) and under the canola compared to the wheat.

---

\(^1\) the Deficit irrigation treatment was not measured because of insufficient tensiometers.
Figure 4-15. The change in total hydraulic potential ($H$) during the spring period in 1998 at three depths under the wheat and canola in $I_0$, $I_1$ and $I_{full}$ in Site 1a. The symbols indicate sample times when there was a significant difference in $H$ between the wheat and the canola at a given depth within an irrigation treatment (i.e. ▲ $I_1$; ● $I_0$). Error bars indicate the least significant differences of means at the 5% level for the time×crop×irrigation interaction.
4.11 **Depth to water table**

### 4.11.1 1998

The average water table depth in Site 1a during the growing season in 1998 is shown below in Figure 4-16. At no time during the monitoring period did the watertable rise to within 2.0 m of the surface. The watertable was highest (2.13 m) around the time of the irrigation on the 2nd June and then fell steadily at an average rate of 2.7 mm day$^{-1}$ ($R^2 = 0.68$, $P < 0.05$) during the winter period until the first spring irrigation (8th Sept). The Murray Irrigation Limited channel system was filled on the 22nd August; the adjacent irrigation bay was watered on the 16th September; and an adjoining paddock was flooded for growing rice on the 15th October.

![Figure 4-16. Average depth of the watertable below the soil surface in Site 1a during 1998. Rainfall (right axis) and irrigations (arrows) are also shown. Error bars are s.e. of the mean (n=4).](image)

### 4.11.2 1999

No water was observed in the test-wells in Site 2 in 1999, indicating that the watertable beneath the site was deeper than 2.8 m for the duration of the experiment.
4.12 Depth of applied water

4.12.1 Site 1a in 1998

The depth of irrigation water applied ($I_a$) to each treatment in Site 1a in 1998 is shown in Table 4-10, together with the amount of rain ($P$) and the change in profile water content ($\Delta S$) between sowing and PM. The estimated depth of run-off ($RO$) from the W_FULL plots after the 56 mm of rain on the 11th November is also shown.

Autumn irrigation

$I_a$ in the autumn pre-irrigations was not measured. However, $\theta_v$ was measured in all plots on 2nd June immediately prior to the third autumn irrigation and then again 24 hours later. The measured change in profile water content (0 to 1 m) resulting from this irrigation was $35 \pm 1$ mm (± s.e. mean, $n = 24$). $ET_o$ on the 2nd June was 2 mm and 1 mm was estimated to have been lost as deep percolation (from water table rise - see Section 4.14.1), so the gross depth of applied water ($I_a$) was estimated to have been 38 mm. Tail-water losses were presumed to be negligible as the supply was stopped before the advance front reached the end of the irrigation bay.

Spring irrigation

Averaged over all plots and irrigations, $55 \pm 1$ mm (± s.e. mean, $n = 42$) of water per irrigation was applied to the plots in Site 1a in 1998. This was 16 mm more water per irrigation than was measured by the NMM for the corresponding change in $\Delta S$ to 1.0 m depth. This difference was due to evaporative losses on the day of irrigation and deep percolation. As the season progressed, soil cracks in the inter-plot space opened and there was clear evidence that significant lateral flows occurred from some plots during the final irrigation of the Full treatment on the 5th November (Figure 4-17). Lateral flows were negligible for the earlier irrigations as the soil in the inter-plot space was not appreciably cracked. Given this, the average depth of irrigation water applied to the Full irrigation treatments in the first three spring irrigations (i.e. 53 mm) was assumed to have been applied in the fourth irrigation on the 5th November, with 10 mm lost in lateral flows across the plot boundary (Table 4-10).
Table 4-10. The mean depth of irrigation water applied ($I_a$) to each treatment in Site 1a in 1998 and the date it was applied, along with the depth of rainfall ($P$), the change in profile water content to 1.0 m ($\Delta S$) and runoff ($RO$) between sowing and PM for each treatment. The total depth of water applied ($W_A$) is calculated from ($I_a + P$) – ($\Delta S + RO$). All values are in mm equivalent depths of water and have been rounded to the nearest mm. Values in parentheses are the s.e. of the mean ($n = 3$).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2 Jun</th>
<th>8 Sept</th>
<th>10 Oct</th>
<th>16 Oct</th>
<th>24 Oct</th>
<th>5 Nov</th>
<th>Total $I_a$</th>
<th>$P$</th>
<th>$\Delta S$</th>
<th>$RO$</th>
<th>$W_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_0</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>38</td>
<td>198</td>
<td>-82</td>
<td></td>
<td>318</td>
</tr>
<tr>
<td>C_1</td>
<td>38</td>
<td>48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>86</td>
<td>202</td>
<td>-90</td>
<td></td>
<td>378</td>
</tr>
<tr>
<td>C_Def</td>
<td>38</td>
<td>49</td>
<td>61</td>
<td></td>
<td></td>
<td></td>
<td>148</td>
<td>202</td>
<td>-77</td>
<td></td>
<td>427</td>
</tr>
<tr>
<td>C_Full</td>
<td>38</td>
<td>53</td>
<td>58</td>
<td>50</td>
<td>64</td>
<td></td>
<td>252</td>
<td>202</td>
<td>-25</td>
<td></td>
<td>479</td>
</tr>
<tr>
<td>W_0</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>38</td>
<td>198</td>
<td>-99</td>
<td></td>
<td>335</td>
</tr>
<tr>
<td>W_1</td>
<td>38</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>88</td>
<td>202</td>
<td>-88</td>
<td></td>
<td>378</td>
</tr>
<tr>
<td>W_Def</td>
<td>38</td>
<td>53</td>
<td>68</td>
<td></td>
<td></td>
<td></td>
<td>159</td>
<td>259</td>
<td>-16</td>
<td></td>
<td>434</td>
</tr>
<tr>
<td>W_Full</td>
<td>38</td>
<td>50</td>
<td>59</td>
<td>50</td>
<td>62</td>
<td></td>
<td>250</td>
<td>259</td>
<td>-4</td>
<td></td>
<td>503</td>
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<tr>
<td>Mean</td>
<td>51</td>
<td>59</td>
<td>65</td>
<td>50</td>
<td>53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 10 mm was estimated to have been lost as lateral flow during irrigation of the Full treatment on the 5th November.
Figure 4-17. Mean water contents (m m\(^{-1}\)) under (a) the wheat and (c) the canola in I\(_0\) and I\(_1\) on the 4\(^{th}\) and 10\(^{th}\) November 1998 showing no change in water content. Evidence of lateral flows from adjacent irrigated plots (2-4 and 3-1) is provided by the increase in \(\theta\) in (b) plot 1-4 and (d) plot 2-1 between the 4\(^{th}\) and 10\(^{th}\) November. Error bars show ± se mean (n=5).
### 4.12.2 Site 1b in 1999

The amount of water applied to Site 1b in 1999 was not measured because of a lack of suitable flow measuring equipment. From the measurements of $I_o$ on this soil type in 1998, it was assumed that 100 mm was applied in the pre-irrigation on the 4\textsuperscript{th} March and then 55 mm in each of the three spring irrigations. Rainfall from the 4\textsuperscript{th} March to PM was 225 mm for the canola and 241 mm for the wheat. $W_A$ was thus assumed to be 490 mm for the canola and 506 mm for the wheat.

### 4.12.3 Site 2 in 1999

The total depth of water applied to each treatment in Site 2 in 1999 between the pre-irrigation on 25\textsuperscript{th} February and PM is shown in Table 4-11. $\theta_v$ was not measured prior to the February pre-irrigation so the following assumptions were made:

- Whitfield (2001) found that profile water contents in autumn were similar to those in December for a range annual crops and pastures in the Murray Valley, so $\Delta S$ in the $W_{\text{Full}}$ and $C_{\text{Full}}$ treatments was assumed to be 0.
- The $W_0$ and $C_0$ treatments held 31 and 15 mm less water (0 to 1.3 m) than the $W_{\text{Full}}$ and $C_{\text{Full}}$ treatments respectively at the end of the season (7\textsuperscript{th} Dec) so $\Delta S$ in the $W_0$ and $C_0$ treatments was taken to be -31 and -15 mm respectively.
- Given the exceptionally wet October, $\Delta S$ in $I_0$ and $I_1$ was assumed to be similar, as was $\Delta S$ in $I_{\text{Def}}$ and $I_{\text{Full}}$.

#### Autumn irrigation

The generally accepted “rule of thumb” is that pre-irrigation of Murray Valley soils uses 150 mm of water (Faour 2001). This is supported by farmer experience over a number of seasons on a range of soil types (M. McBurnie, pers. comm. 2004). It was assumed this depth of water was applied to Site 2 in the pre-irrigation on 25\textsuperscript{th} February 1999.

#### Spring irrigation

Averaged over all plots and irrigations, $78 \pm 2$ mm (± s.e. mean, n = 41) of water per irrigation was applied to the Cobram loam in 1999 (Table 4-11). This was, on average, 34 mm more water per irrigation than was measured by the NMM for the corresponding increase in profile water content to 1.3 m depth in the $W_{\text{Full}}$ and $C_{\text{Full}}$ plots.
Table 4-11. The mean depth of irrigation applied ($I_a$), rainfall ($P$) and the change in profile water content to 1.3 m ($\Delta S$) between 25\textsuperscript{th} February and PM for each treatment in Site 2 in 1999 (units = mm). $W_A = (I_a + P) - \Delta S$. Values in parentheses are s.e. of the mean ($n = 4$, except $W_F$ where $n = 3$).

<table>
<thead>
<tr>
<th>Treat</th>
<th>25 Feb</th>
<th>18 Sep</th>
<th>16 Oct</th>
<th>22 Oct</th>
<th>11 Nov</th>
<th>Total $I_a$</th>
<th>$P$</th>
<th>$\Delta S$</th>
<th>$W_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_0$</td>
<td>150</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
<td>225</td>
<td>-15</td>
<td>390</td>
</tr>
<tr>
<td>$C_1$</td>
<td>150</td>
<td>75 (3.2)</td>
<td></td>
<td></td>
<td></td>
<td>225</td>
<td>225</td>
<td>-15</td>
<td>465</td>
</tr>
<tr>
<td>$C_{Def}$</td>
<td>150</td>
<td>84 (6.0)</td>
<td>81 (5.0)</td>
<td></td>
<td></td>
<td>316</td>
<td>225</td>
<td></td>
<td>541</td>
</tr>
<tr>
<td>$C_{Full}$</td>
<td>150</td>
<td>88 (10.6)</td>
<td>64 (3.2)</td>
<td></td>
<td></td>
<td>302</td>
<td>225</td>
<td>*</td>
<td>527</td>
</tr>
<tr>
<td>$W_0$</td>
<td>150</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
<td>225</td>
<td>-31</td>
<td>406</td>
</tr>
<tr>
<td>$W_1$</td>
<td>150</td>
<td>87 (8.2)</td>
<td></td>
<td></td>
<td></td>
<td>237</td>
<td>241</td>
<td>-31</td>
<td>509</td>
</tr>
<tr>
<td>$W_{Def}$</td>
<td>150</td>
<td>90 (4.7)</td>
<td>87 (1.8)</td>
<td></td>
<td></td>
<td>326</td>
<td>241</td>
<td></td>
<td>567</td>
</tr>
<tr>
<td>$W_{Full}$</td>
<td>150</td>
<td>77 (8.3)</td>
<td>59 (2.4)</td>
<td>57 (2.2)</td>
<td></td>
<td>342</td>
<td>241</td>
<td></td>
<td>583</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>84 (2.9)</td>
<td>62 (2.2)</td>
<td>84 (2.7)</td>
<td>57 (2.2)</td>
</tr>
</tbody>
</table>

* 16 mm of rain on 21/11/1999 was not considered to have contributed to canola yield in this treatment

The lighter texture of the soil in Site 2 ensured appreciable cracking did not occur and evidence of lateral flows was not observed. NMM readings prior to the irrigation of the Full treatment on the 16\textsuperscript{th} October 1999 and then again 36 hours later showed water content increased at all depths measured in the profile (Figure 4-18). This increase in count ratio at all depths suggests that the discrepancy between $I_a$ and $\Delta S$ in Site 2 was due to water draining below the lowest NMM reading (i.e. 120 cm).

Figure 4-18. NMM count ratio profiles under the canola ($C_{Full}$, left) and the wheat ($W_{Full}$, right) taken before and after an irrigation on the 16\textsuperscript{th} October in Site 2 in 1999.
4.13 Crop response to irrigation

Figure 4-19 shows the relationship between treatment average grain yield \((Y)\) and the total depth of water applied \((W_A)\) to each treatment for both Years and Sites. Step-wise multiple linear regression analysis in GENSTAT showed that there was a very strong linear relationship between \(Y\) and \(W_A\) within each crop type \((R^2 = 0.965; \text{ se obs. } = 0.299; \ P < 0.001)\). The relationships for each crop indicate that yields increased by 9 kg ha\(^{-1}\) per mm of \(W_A\) in the wheat and by 3 kg ha\(^{-1}\) per mm of \(W_A\) in the canola as \(W_A\) increased from approximately 300 to 600 mm. The analysis showed there was no significant Site/Year effect on these relationships.

\[
Y = 1.88 + 0.0089 \times W_A
\]

\(R^2 = 0.83\)

\[
Y = 1.92 + 0.0029 \times W_A
\]

\(R^2 = 0.66\)

Figure 4-19. The relationship between grain yield \((Y; \text{ t ha}^{-1})\) and total applied water \((W_A; \text{ mm})\) for the wheat and canola crops grown in Site 1a in 1998 and Sites 2 and 1b in 1999.

In order to assess the yield response to spring irrigation, the relationship between \(Y\) and the depth of water applied to each plot (i.e. \(P + I_o\)) from the first spring irrigation to PM \((W_S)\) was also examined. Step-wise multiple linear regression analysis showed there was a highly significant correlation between \(Y\) and \(W_S\) within each crop type \((R^2 = 0.97; \text{ se obs. } = 0.25; \ P < 0.001; \text{ see Table 4-12 and Figure 4-20})\). The grain yield responses to \(W_S\) of the two crops were significantly different, with wheat yield increasing 4.6 kg ha\(^{-1}\) per mm of \(W_S\) and canola yield increasing 1.9 kg ha\(^{-1}\) per mm \(W_S\). It is of note that the slope of the relationship between \(Y\) and \(W_S\) in the canola only differed significantly from zero at the 10% level. The results of the regression analysis (Table 4-12) show that there was
no significant Site/Year effect in the canola. There was also no significant Site/Year effect on the rate of increase in $Y$ per mm $W_S$ in the wheat. However, wheat yields from Site 2 in 1999 were significantly greater (by 1.2 t ha$^{-1}$) than those from Site 1a in 1998.

Table 4-12. Estimates of the parameters from the linear regression of plot yield (t ha$^{-1}$) on depth of water applied in rainfall and irrigation in the spring period ($W_S$; mm) to the wheat and the canola in Site 1a in 1998 and Site 2 in 1999. Differences in the parameters were assessed in comparison to a reference level, which was the canola in Site 1a. The regression model had the form:

$$\text{Constant} + W_S + \text{crop} + \text{site} + W_S \times \text{crop} + W_S \times \text{site} + \text{crop.site} + W_S \times \text{crop.site}.$$ 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>s.e.</th>
<th>t (n=46)</th>
<th>t prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>2.734</td>
<td>0.168</td>
<td>16.24</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>$W_S$</td>
<td>0.00164</td>
<td>0.00089</td>
<td>1.84</td>
<td>0.073 ns</td>
</tr>
<tr>
<td>wheat</td>
<td>1.579</td>
<td>0.231</td>
<td>6.84</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>site 2</td>
<td>0.186</td>
<td>0.265</td>
<td>0.70</td>
<td>0.485 ns</td>
</tr>
<tr>
<td>$W_S \times$ wheat</td>
<td>0.00354</td>
<td>0.00114</td>
<td>3.10</td>
<td>0.003</td>
</tr>
<tr>
<td>$W_S \times$ site 2</td>
<td>0.00048</td>
<td>0.00130</td>
<td>0.37</td>
<td>0.711 ns</td>
</tr>
<tr>
<td>wheat $\times$ site 2</td>
<td>1.224</td>
<td>0.375</td>
<td>3.26</td>
<td>0.002</td>
</tr>
<tr>
<td>$W_S \times$ wheat $\times$ site 2</td>
<td>-0.00172</td>
<td>0.00170</td>
<td>-1.01</td>
<td>0.319 ns</td>
</tr>
</tbody>
</table>

Figure 4-20. The relationship between grain yield and the depth of water applied in rainfall and irrigation in the spring period to the wheat and canola plots in Site 1a in 1998 and Site 2 in 1999 ($R^2 = 0.97$; se obs = 0.25; $P < 0.001$). Yields have been adjusted to account for Site/Year differences in the intercept. Slopes are 4.6 kg ha$^{-1}$ mm$^{-1}$ for the wheat and 1.9 kg ha$^{-1}$ mm$^{-1}$ for the canola.
4.14 Vertical water fluxes

4.14.1 Watertable response

The general rate of fall in the watertable under Site 1a during the winter period in 1998 (i.e. 2.7 mm day\(^{-1}\), Section 4.11.1) was used to calculate the height of watertable rise following four mid-winter (21\(^{st}\) June, 23\(^{rd}\) June, 20\(^{th}\) July, 25-28\(^{th}\) July) and two spring (21-23\(^{rd}\) Sept, 11\(^{th}\) Nov) rainfall events. Losses in the spring rainfall events were greater than in the mid-winter events so a single straight line did not eventuate when watertable rise was plotted on event rainfall. However, all six points did fall on a straight line through the origin when losses (i.e. \(ET_o\), \(\Delta S\) and \(RO\)) were accounted for (Figure 4-21). The specific yield (\(S_y\)), as given by the slope of the line of best fit, was found to be 0.057 mm mm\(^{-1}\) (\(R^2 = 0.97\)).

![Figure 4-21. Estimated deep percolation due to six rainfall events in 1998 plotted against the watertable rise due to those events. The specific yield (\(S_y\)), as given by the slope of the line of best fit through the origin, is 0.057 mm mm\(^{-1}\) (\(R^2 = 0.97\)).](image)

The height of each watertable rise during the winter period was calculated (assuming the falling limb of the test-well hydrograph fell at a rate of 2.7 mm day\(^{-1}\)) and the total watertable rise was found to be 630 mm. The amount of deep percolation (\(DP\)) during the winter period from 2\(^{nd}\) June to the 8\(^{th}\) September was estimated (using Equation 3-12) to be 36 mm.
4.14.2 Darcian flux calculations

Table 4-13 shows total water fluxes across a plane at 100 cm for the period from 20th August to 6th October 1998. Treatments were not significantly different, largely because of the variability in the data. Plot 3-6 (C0) in particular caused a non-normal distribution of the residuals. Re-analysis with this plot set as missing showed that irrigation frequency but not crop type had a significant effect on total water flux. Plots 3-5 and 3-8 were also aberrant. All three of these plots were in the north-east corner of Site 1a and it is possible that the sub-soil in this area was different to the rest of the experimental site.

Table 4-13. Total water flux (mm, positive downwards) between 80 and 120 cm below the wheat and the canola in I0, I1 and IFull in Site 1a over the period 20th August to 6th October 1998. Values in brackets are the standard error of the mean.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>-5</td>
<td>-9</td>
<td>-41</td>
<td>-18 (11.3)</td>
</tr>
<tr>
<td>C1</td>
<td>-5</td>
<td>-5</td>
<td>-6</td>
<td>-5 (0.3)</td>
</tr>
<tr>
<td>CFull</td>
<td>7</td>
<td>6</td>
<td>-3</td>
<td>3 (3.1)</td>
</tr>
<tr>
<td>W0</td>
<td>-2</td>
<td>-10</td>
<td>-18</td>
<td>-10 (4.6)</td>
</tr>
<tr>
<td>W1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0 (0.3)</td>
</tr>
<tr>
<td>WFull</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2 (0.4)</td>
</tr>
</tbody>
</table>

Readings from tensiometers at 80 cm in I0 and I1 were unreliable after the 6th October because they exceeded 800 mbar (Bond 1998). To gain an estimate of water fluxes for the entire spring period, hydraulic gradients were calculated between 100 and 120 cm (Figure 4-22). The same moisture characteristic applied to these depths so $K(\theta)$ was determined from Equation 3-9 using the average of the moisture contents at 100 and 120 cm depth.

The ANOVA results (Table 4-14) confirmed that irrigation treatment had a significant effect on vertical fluxes in spring in 1998, with capillary rise ($CR$) significantly greater in I0 compared to IFull. The trends for greater CR under the canola also persisted but this difference was only significant in I0. Significant differences between the hydraulic gradients under the two crops developed late in the season in the I0 and I1 treatments (Figure 4-22). This supports the contention that CR was also greater under the canola in the I1 treatment.
Table 4-14. Total water flux (mm, positive downwards) between 100 and 120 cm in each plot in Site 1a during the period 8\textsuperscript{th} September to 10\textsuperscript{th} November 1998. Significance of differences between means: crop, P= 0.08; irrigation, P=0.02; crop\times irrigation, P=0.62. Different superscripts after each mean show significant differences (5\% lsd for the crop\times irrigation interaction = 39 mm).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{0}</td>
<td>-24</td>
<td>-54</td>
<td>-160</td>
<td>-79 \textsuperscript{a}</td>
</tr>
<tr>
<td>C\textsubscript{1}</td>
<td>-49</td>
<td>-52</td>
<td>-45</td>
<td>-49 \textsuperscript{ab}</td>
</tr>
<tr>
<td>C\textsubscript{Full}</td>
<td>-4</td>
<td>-3</td>
<td>-9</td>
<td>-6 \textsuperscript{cd}</td>
</tr>
<tr>
<td>W\textsubscript{0}</td>
<td>-13</td>
<td>-58</td>
<td>-46</td>
<td>-39 \textsuperscript{bc}</td>
</tr>
<tr>
<td>W\textsubscript{1}</td>
<td>-22</td>
<td>-8</td>
<td>-10</td>
<td>-13 \textsuperscript{bcd}</td>
</tr>
<tr>
<td>W\textsubscript{Full}</td>
<td>-3</td>
<td>12</td>
<td>-3</td>
<td>2 \textsuperscript{d}</td>
</tr>
</tbody>
</table>

Figure 4-22. Treatment average hydraulic gradient between 100 and 120 cm under the wheat and the canola in I\textsubscript{Full} (top), I\textsubscript{1} (middle) and I\textsubscript{0} (bottom) treatments in Site 1a between 19\textsuperscript{th} August and 10\textsuperscript{th} November 1998. Error bars show the least significant difference of the means (5\%). Gradients are positive downwards and the scale has been reversed for ease of interpretation.
## 4.15 Water balance

Table 4-15 shows the components of the water balance that were measured in the various treatments in Site 1a during the winter and spring periods in 1998. Crop water use ($ET_c$) was calculated for each period according to Equation 3-6 and summed to obtain total $ET_c$ for each treatment from sowing to PM.

### Table 4-15. Estimates of the components of the water balance equation (mm) for the treatments in Site 1a during the 1998 growing season. For CR, vertical fluxes are positive downwards.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>$ET_o$</th>
<th>$P$</th>
<th>$I_a$</th>
<th>$\Delta S$</th>
<th>$DP$</th>
<th>$CR^{(1)}$</th>
<th>$RO$</th>
<th>$ET_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Winter period: sowing to first spring irrigation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>canola</td>
<td>190</td>
<td>125</td>
<td>38</td>
<td>-33</td>
<td>33</td>
<td>0</td>
<td>162</td>
<td></td>
</tr>
<tr>
<td>wheat</td>
<td>190</td>
<td>125</td>
<td>38</td>
<td>-31</td>
<td>35</td>
<td>0</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td><strong>Spring period: first spring irrigation to PM $^{(2)}$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_0$</td>
<td>178</td>
<td>74</td>
<td>0</td>
<td>-49</td>
<td>0</td>
<td>-79</td>
<td>0</td>
<td>201</td>
</tr>
<tr>
<td>$C_1$</td>
<td>239</td>
<td>78</td>
<td>51</td>
<td>-57</td>
<td>19</td>
<td>-49</td>
<td>0</td>
<td>215</td>
</tr>
<tr>
<td>$C_{Def}$</td>
<td>242</td>
<td>78</td>
<td>111</td>
<td>-44</td>
<td>28</td>
<td>-27</td>
<td>0</td>
<td>232</td>
</tr>
<tr>
<td>$C_{Full}$</td>
<td>242</td>
<td>78</td>
<td>213</td>
<td>8</td>
<td>50</td>
<td>-6</td>
<td>0</td>
<td>239</td>
</tr>
<tr>
<td>$W_0$</td>
<td>209</td>
<td>74</td>
<td>0</td>
<td>-68 $^{(5)}$</td>
<td>0</td>
<td>-39</td>
<td>0</td>
<td>180</td>
</tr>
<tr>
<td>$W_1$</td>
<td>239</td>
<td>78</td>
<td>51</td>
<td>-56</td>
<td>17</td>
<td>-13</td>
<td>0</td>
<td>181</td>
</tr>
<tr>
<td>$W_{Def}$</td>
<td>268</td>
<td>134</td>
<td>119</td>
<td>15</td>
<td>31</td>
<td>-6 $^{(4)}$</td>
<td>0</td>
<td>213</td>
</tr>
<tr>
<td>$W_{Full}$</td>
<td>268</td>
<td>134</td>
<td>212</td>
<td>27</td>
<td>68</td>
<td>2</td>
<td>10</td>
<td>239</td>
</tr>
</tbody>
</table>

1. estimated using Darcian flux calculations for period 8th Sept to 10th Nov (from Table 4-14).
2. Dates of PM: $C_0$ = 29th Oct, $W_0$ = 4th Nov, $C_1$ & $W_1$ = 10th Nov; $C_{Def}$ & $C_{Full}$ = 12th Nov; $W_{Def}$ & $W_{Full}$ = 17th Nov
3. 56 mm of rain that fell on the 11th November is not included in this total as it was not considered to have contributed to canola yield in these treatments. $\Delta S$, $DP$ and $RO$ have been adjusted accordingly.
4. $CR$ in the Deficit irrigation treatments were estimated to be the average $CR$ of the 1 and Full irrigation treatments
5. The profile water content ($S$) on the 4th November was used in the calculation of $\Delta S$ because lateral flows from plots irrigated on the 5th November caused $S$ to increase between the 4th and 10th November.

There was no significant difference in $\Delta S$ (Section 4.9.1) between the two crops in the winter period and only a 2.6 mm difference in $DP$. The 4mm difference in $ET_c$ for this period is insignificant given the measurement errors involved. Vertical fluxes in the winter period were predominantly downwards (excess rainfall, wet soil, low $E$ and small plants) and it is seen that $DP$ calculated using the water balance approach (Table 4-15) is in good agreement with $DP$ estimated using watertable response (page 91).
There was no significant difference in the profile water contents (0-1 m) of the two crops within each irrigation treatment at any time during the spring period. The inter-crop differences in $\Delta S$ shown in Table 4-15 thus reflect differences in the time taken to reach PM. This is highlighted by the similarity in $\Delta S$ between the wheat and the canola in the 1 irrigation treatments, which reached PM around the 10th November, and the positive values for $\Delta S$ in the W Def and the W Full treatments, which reached PM after 56 mm of rain fell on the 11th November. Vertical fluxes were thus the major components of the water balance that were affected by the crop and irrigation treatments.

The rapid rises in the watertable following large rainfall events (Figure 4-16) support the assumption that macro-pore flows comprised the major contribution to $DP$ in spring. It was considered that these flows were well accounted for by the water balance approach but were mostly missed by the Darcian flux method because they either bypassed the tensiometers, which respond mainly to the water potential of the soil matrix (Shaw, et al. 1990), or occurred too quickly to be picked up with readings every 2-3 days. The tensiometers did measure the gradual increase in upward hydraulic gradient in $I_0$ and $I_1$ and this was the major process contributing to $CR$ in the spring period. Net vertical flux in the spring period was thus calculated as the difference between $DP$ from water balance calculations and $CR$ from Darcian flux calculations.

Examination of Table 4-15 shows that both crop type and irrigation frequency influenced $ET_c$. These effects can be summarised in a general fashion as follows:

- $\Delta S$ increased with decreasing irrigation frequency
- $DP$ increased with increasing irrigation frequency
- $CR$ increased with decreasing irrigation frequency
- $CR$ was greater under the canola

The cumulative result of these effects was that the canola used approximately 20-30 mm more water than the wheat in all treatments except $I_{Full}$. The main reason for this difference was the greater ability of the canola to extract deep soil moisture (as shown in Sections 4.9 and 4.10) and this resulted in lower $DP$ and greater $CR$ under the canola in all irrigation treatments. The similar $ET_c$ in the $C_{Full}$ and $W_{Full}$ treatments was due to the later maturity of the wheat which resulted in 56 mm of rain on 11th November being included in the water balance of the $W_{Full}$ and not the $C_{Full}$ treatment.
4.16 Crop coefficients ($K_c$) and growth stage lengths

The values of $K_c$ calculated for the wheat and the canola in Site 1a during the 1998 growing season are shown in Figure 4-23. Irrigation extended the late season stage in the wheat and extended both the mid-season and, to a lesser extent, the late season stage in the canola. Drought stress in the I0 during mid-September is evidenced by lower $K_c$ values in this treatment at that time, with the lower $K_c$ for C0 indicating a greater degree of drought stress in the canola. Water use in both C0 and W0 recovered following the 42 mm of rain on the 21-23 September.

![Crop growth stages and measured crop coefficients ($K_c$) for the wheat (top) and the canola (bottom) in Site 1a during the 1998 growing season. Each point shows the mean $K_c$ for a 7-10 day period and is located in the middle of that period. Refer to the text for further details.](image)

Figure 4-23. Crop growth stages and measured crop coefficients ($K_c$) for the wheat (top) and the canola (bottom) in Site 1a during the 1998 growing season. Each point shows the mean $K_c$ for a 7-10 day period and is located in the middle of that period. Refer to the text for further details.
4.16.1 Initial stage ($K_{c \text{ ini}}$)

The initial stage runs from sowing to approximately 10% ground cover (Allen, et al. 1998). Ten percent ground cover was taken as occurring when GLA = 1 in the wheat, which was on the 16th June in 1998. In the canola, GLA = 1 occurred on 30th July but observations indicated 10% cover occurred on the 7th July so this date was used instead. $K_{c \text{ ini}}$ averaged 0.7 from sowing to early July in the wheat and averaged 0.8 from sowing to early August in the canola. These values agree with those given by Allen, et al. (1998) for conditions similar to those that occurred during winter in 1998 (i.e. weekly wetting events of 10-40 mm at a time when $ET_o$ is 1-3 mm day$^{-1}$) and were used to derive the curves in Figure 4-23. The dashed lines in the crop coefficient curves in Figure 4-23 show $K_{c \text{ ini}}$ values of 0.3 for wheat and 0.35 for canola. These are taken from Allen, et al. (1998) and are shown for comparative purposes.

4.16.2 Mid-season stage ($K_{c \text{ mid}}$)

The mid-season stage runs from effective full cover to the start of maturity (Allen, et al. 1998). In this case it was assumed to begin when GLA = 3 and to finish at the end of flowering. However, this only applied to the wheat and the mid-season stage was assessed to run from the 3rd August to the 6th October (i.e. 64 days). Spring irrigation extended the duration of green leaves in the canola by approximately 10 days after flowering had finished, so the mid-season stage in CFull (and probably CDef) was assessed as running from the 22nd August to the 12th October (i.e. 52 days). In contrast to this, green leaves were not retained in C0 and C1 past the end of flowering so that the end of the mid-season stage in these treatments did coincide with the end of flowering (3rd October).

From the 20th August until the first spring irrigation on the 8th September there was a zero flux plane at 100 cm (Section 4.10, page 81) and the crops were not considered to be water stressed. Changes in profile water content ($\Delta S; 0$–1.0 m) during this period therefore reflected maximum crop water use and $K_{c \text{ mid}}$ was calculated from this data to be 1.2 for the wheat and 1.15 for the canola (Table 4-16).
Table 4-16. Potential ($ET_o$) and actual ($ET_c$) evapotranspiration (mm) by the wheat and canola crops in Site 1a between the 13th August and 8th September 1998 and the mid-season crop factor for each crop calculated from this data ($K_{c\,\text{mid}} = ET_c/ET_o$).

<table>
<thead>
<tr>
<th>Period</th>
<th>canola</th>
<th>wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ET_o$ (mm)</td>
<td>$ET_c$ (mm)</td>
</tr>
<tr>
<td>13/8 to 22/8</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>23/8 to 31/8</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>1/9 to 8/9</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.16.3 Late season stage ($K_{c\,\text{end}}$)

The late season stage in $I_{\text{Full}}$ was assessed to end at harvest. This occurred on the 27th and the 20th November for the $W_{\text{Full}}$ and $C_{\text{Full}}$ treatments respectively. Allen, et al. (1998) give values for $K_{c\,\text{end}}$ of 0.25 for wheat and 0.35 for canola and these values fitted the data well (Figure 4-23). The late season stage in $I_0$ and $I_1$ ended in early November for the wheat and possibly slightly earlier for the canola. The end of the late season stage in $I_{\text{Def}}$ was intermediate between $I_0$ and $I_1$ and the $I_{\text{Full}}$ treatment.

The crop factors presented in Figure 4-23 are based on water balance calculations that don’t include the $CR$ that occurred during the late season stage under both crops. This will have resulted in underestimation of $K_c$ in $I_0$, $I_1$ and $I_{\text{Def}}$ in the late season stage. However, as shown in Figure 4-22 (page 93), upward fluxes into the root zone in $I_{\text{Full}}$ were small throughout the spring period, so the derived crop coefficient curves are considered to accurately reflect conditions for well watered (i.e. non-stressed) wheat and canola crops in the Murray Valley.
Chapter 5. Discussion

5.1 Optimal levels of irrigation

5.1.1 Crop production functions

The primary objective of this thesis was to determine the relationship between yield and applied water for the major irrigated winter crops in the NSW central Murray Valley. Generalised crop production functions for flood irrigated canola (Figure 5-1) and wheat (Figure 5-2) were constructed using the data from this experiment and the experiments of Cooper (1980b) on wheat at Yanco, NSW; Steiner et al. (1985) on wheat at Griffith NSW; and Taylor, et al. (1991) on canola at Tatura, Vic. Yield and rainfall data from well managed dryland crops grown at Deniliquin was obtained from farmer records to construct the lower limb of these curves (Ian Lea, “Wynlea”, pers. comm.). It was presumed that the $S$ under these dryland crops was similar in April and November (Whitfield 2001). It is considered that the inclusion of the data from these other sources makes these production functions broadly representative of flood irrigated wheat and canola crops in the irrigation districts of the southern MDB.

These quadratic production functions are similar to the production functions used by English & Nakamura (1989) and found for wheat by English & Raja (1996) and Zhang & Oweis (1999). They support Stewart and Hagan’s (1973) explanation for the nature of the $Y-W_A$ relationship for flood irrigated crops. The linear $Y-ET$ relationship and the curvilinear $Y-W_A$ relationship intersect at the long term median April to October rainfall for Deniliquin (250 mm: BoM 2007) and the average district yield (2.7-2.8 t ha$^{-1}$ for wheat and 1.5-1.7 t ha$^{-1}$ for canola; ABARE 1998; ABS 2001). As irrigation water is applied ($W_A > 250$ mm), non-$ET$ losses reduce irrigation efficiency and cause the $Y-W_A$ curves to become convex.

The straight line potential $Y-ET$ relationships for the wheat ($T_e = 20$ kg ha$^{-1}$ mm$^{-1}$, $E = 110$ mm) and the canola ($T_e = 15$ kg ha$^{-1}$ mm$^{-1}$, $E = 130$ mm) are identical to those given by French (1995) except that $E$ in the canola is 20 mm higher. Hocking et al. (1997a) suggested that $T_e$ for oilseeds was 12.5 kg ha$^{-1}$ mm$^{-1}$, however Robertson & Kirkegaard (2005) found 15 kg ha$^{-1}$ mm$^{-1}$ was the upper envelope for the $Y-ET$ relationship for
canola in southern NSW and that canola yield potential reached a limit at a seasonal water supply of 450 mm. They also found a higher intercept for canola (120 mm) than suggested by French (1995), stating this was physiologically justified because lower early vigour and slower canopy development resulted in greater soil evaporation losses.

Non-ET losses from irrigation (i.e. $W_A > 250$ mm) are attributed to deep percolation and unused soil water, as there was no runoff in the experiments from which these curves were derived. Given that most irrigators recycle their tail-water (Murray Irrigation Limited 2003), these curves are considered representative of district ‘best practice’ at the paddock level. They do not included transmission/storage losses from farm supply channels and dams, so it is likely that the $Y-W_A$ relationship for a farm will be more convex. However, these losses vary greatly between and within farms because of differences in irrigation infrastructure and management. By excluding transmission losses, it is considered that a fairer comparison of cropping options at the paddock scale will be made.

\[
Y = -3.40 + 2.59 \times 10^{-2} W_A - 2.44 \times 10^{-5} W_A^2 \quad (R^2 = 0.915)
\]

The vertical line shows long term median April-October rainfall at Deniliquin (Clewett et al. 1999) and the horizontal line shows average district canola yield (ABS 2001). Data from Tasmania (▲, Mendham, et al. 1984) was used to help define the upper envelope shown by the dashed line: i.e. $T_c$ for grain of 15 kg ha$^{-1}$ mm$^{-1}$ and an intercept on the x-axis of 130 mm.

![Graph showing grain yield (Y) as a function of seasonal applied water (W_A) for canola in the irrigation districts of southern NSW. The regression line is fitted to data from irrigation experiments at Deniliquin (○, this experiment) and Tatura, Vic, (Δ, Taylor, et al. 1991) and from farmer records for dryland crops grown at Deniliquin between 1995 and 2004 (●, Ian Lea, pers. comm.). It has the form: \[ Y = -3.40 + 2.59 \times 10^{-2} W_A - 2.44 \times 10^{-5} W_A^2 \quad (R^2 = 0.915) \] The vertical line shows long term median April-October rainfall at Deniliquin (Clewett et al. 1999) and the horizontal line shows average district canola yield (ABS 2001). Data from Tasmania (▲, Mendham, et al. 1984) was used to help define the upper envelope shown by the dashed line: i.e. $T_c$ for grain of 15 kg ha$^{-1}$ mm$^{-1}$ and an intercept on the x-axis of 130 mm.](image_url)
Figure 5-2. Grain yield \((Y)\) as a function of seasonal applied water \((W_A = P + I_a + ΔS)\) for wheat in the irrigation districts of southern NSW. The regression line is fitted to data from irrigation experiments at Deniliquin (○, this experiment), Yanco (△, Cooper 1980b) and Griffith (▲, Steiner et al. 1985) and from farmer records for dryland crops grown at Deniliquin between 1983 and 2004 (●, Ian Lea, pers. comm.). It has the form:

\[
Y = -2.25 + 2.30 \times 10^{-2} \cdot W_A - 1.25 \times 10^{-5} \cdot W_A^2 \quad (R^2 = 0.938).
\]

The vertical line shows long term median April-October rainfall at Deniliquin (Clewett et al. 1999) and the horizontal line shows average district wheat yield (ABARE 1998; ABS 2001). The dashed line shows a maximum \(T_e\) for grain of 20 kg ha\(^{-1}\) mm\(^{-1}\) with an intercept on the x-axis at 110 mm.

The data used to derive these curves was obtained from flood irrigated crops so they are therefore not applicable to other irrigation application systems where the nature and magnitude of irrigation losses will differ (e.g. overhead or sub-surface drip systems). Additionally, the curves were derived from crops grown on red brown earth and transitional red brown earth soils (Stace, et al. 1968) and they may not apply to other major soil groups, even though the soils in the data set ranged from relatively well drained soils to less permeable soils suitable for rice. Heavy grey clays of the Riverine plains, for example, have a greater propensity to waterlog (Setter & Waters 2003) and this may reduce the potential to achieve higher yields at higher levels of applied water. For light textured soils, on the other hand, deep percolation losses under flood irrigation may be greater and this will increase the curvature of the \(Y-W_A\) relationship.
### 5.1.2 Cost Functions

Production costs for rainfed and flood irrigated, direct drilled wheat and canola crops in the Murray Valley are shown in Table 5-1. English & Raja (1996) used the two point method to derive a linear cost function from the cost data of unirrigated and irrigated crops. This is not considered realistic here, as a minimum $W_A$ is required for crop production and there is a minimum cost associated with land preparation, sowing and crop establishment. For this analysis, the minimum (fixed) cost was assumed equal to

Table 5-1. Production costs ($ ha$^{-1}$) for unirrigated and irrigated wheat (top) and canola (bottom) in the NSW Murray irrigation districts (Singh, et al. 2007; J. Fowler, NSW DPI, pers. comm.). The cost functions derived from this data are also shown.

<table>
<thead>
<tr>
<th>Wheat - costs per ha</th>
<th>unirrigated</th>
<th>irrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water applied</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 mm</td>
<td>304</td>
<td>541</td>
</tr>
<tr>
<td>500 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Yield - from the production function for wheat</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.7 t ha$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cultivation</strong></td>
<td>$3</td>
<td>$15</td>
</tr>
<tr>
<td><strong>Sowing</strong></td>
<td>$53</td>
<td>$78</td>
</tr>
<tr>
<td><strong>Fertiliser &amp; application</strong></td>
<td>$114</td>
<td>$153</td>
</tr>
<tr>
<td><strong>Herbicide &amp; application</strong></td>
<td>$59</td>
<td>$59</td>
</tr>
<tr>
<td><strong>Insecticide, fungicide &amp; application</strong></td>
<td>$8</td>
<td>$8</td>
</tr>
<tr>
<td><strong>Contract harvesting</strong></td>
<td>$51</td>
<td>$92</td>
</tr>
<tr>
<td><strong>Levies from yield @ crop price</strong></td>
<td>$5</td>
<td>$11</td>
</tr>
<tr>
<td><strong>Crop insurance from yield @ crop price</strong></td>
<td>$11</td>
<td>$24</td>
</tr>
<tr>
<td><strong>Irrigation</strong></td>
<td>$101</td>
<td></td>
</tr>
<tr>
<td><strong>Total costs per ha</strong></td>
<td><strong>$304</strong></td>
<td><strong>$541</strong></td>
</tr>
<tr>
<td><strong>Cost function</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0 &lt; W_A &lt; 250 mm $</td>
<td>$c(W_A) = 304$</td>
<td>$c(W_A) = 304 + 0.95 \times (W_A - 250)$</td>
</tr>
<tr>
<td>$W_A \geq 250 mm$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Canola - costs per ha</th>
<th>unirrigated</th>
<th>irrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water applied</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 mm</td>
<td>328</td>
<td>546</td>
</tr>
<tr>
<td>450 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Yield - from the production function for canola</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6 t ha$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cultivation</strong></td>
<td>$23</td>
<td>$30</td>
</tr>
<tr>
<td><strong>Sowing</strong></td>
<td>$14</td>
<td>$29</td>
</tr>
<tr>
<td><strong>Fertiliser &amp; application</strong></td>
<td>$123</td>
<td>$207</td>
</tr>
<tr>
<td><strong>Herbicide &amp; application</strong></td>
<td>$23</td>
<td>$23</td>
</tr>
<tr>
<td><strong>Insecticide, fungicide &amp; application</strong></td>
<td>$13</td>
<td>$13</td>
</tr>
<tr>
<td><strong>Contract windrowing</strong></td>
<td>$25</td>
<td>$25</td>
</tr>
<tr>
<td><strong>Contract harvesting</strong></td>
<td>$78</td>
<td>$84</td>
</tr>
<tr>
<td><strong>Levies from yield @ crop price</strong></td>
<td>$9</td>
<td>$17</td>
</tr>
<tr>
<td><strong>Crop insurance from yield @ crop price</strong></td>
<td>$20</td>
<td>$37</td>
</tr>
<tr>
<td><strong>Irrigation</strong></td>
<td>$81</td>
<td></td>
</tr>
<tr>
<td><strong>Total costs per ha</strong></td>
<td><strong>$328</strong></td>
<td><strong>$546</strong></td>
</tr>
<tr>
<td><strong>Cost function</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0 &lt; W_A &lt; 250 mm $</td>
<td>$c(W_A) = 328$</td>
<td>$c(W_A) = 328 + 1.09 \times (W_A - 250)$</td>
</tr>
<tr>
<td>$W_A \geq 250 mm$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the cost of production of the unirrigated crop grown on median rainfall (i.e. \( W_A = 250 \) mm). The (variable) cost of irrigation was determined as the slope of the cost function between the unirrigated and irrigated crops. The cost functions so derived are shown in Table 5-1 and illustrated in Figure 5-3. They are indicative only but are considered representative of an “average” farm in the NSW Murray Valley in 2007.

5.1.3 Irrigation Strategies to Maximise Profit

English & Raja’s (1996) methodology was used to determine \( W_A \) for a range of objectives from the revenue and cost functions based on the following assumptions:

- crop price equals the long term average, which is $180 t^{-1}$ for wheat (Wynter & Cooper 2004) and $350 t^{-1}$ for canola (Ontario Ministry of Agriculture 2006);
- crops receive the median growing season rainfall of 250 mm (BoM 2007);
- crops are pre-irrigated in autumn with 100 to 150 mm and spring irrigations apply 60 to 75 mm (Loveday & Scotter 1966; Loveday, et al. 1978; Cockroft & Martin 1981; Hume 1993; Dunbabin, et al. 1997; Giblin & Lacy 2003; Singh, et al. 2007).

The depths of \( W_A \) when yields are maximised (\( W_m \)), when profits are maximised if land is limiting (\( W_l \)) and when profits are maximised if water is limiting (\( W_w \)) are shown in Table 5-2, together with the expected irrigation requirements and yields and the associated net returns per ha and per ML. Figure 5-3 illustrates the profit maximising application depths (\( W_l \) and \( W_w \)) in relation to the revenue and cost functions for each crop.

![Figure 5-3. Cost (- - -) and revenue (▬) functions for wheat (left) and canola (right) in the NSW Murray irrigation districts. The maximum average net return per ML (····) is shown, as are the profit maximising levels of \( W_A \) when land is limiting (\( W_l \)) and when water is limiting (\( W_w \)).](image-url)
Table 5-2. Depths of water to apply ($W_A$; mm) to wheat and canola in the NSW Murray Valley to meet one of three objectives: 1) maximise yield ($W_m$); 2) maximise profit when land is limiting ($W_l$); and 3) maximise profit when water is limiting ($W_w$). Also shown is the total irrigation requirement (i.e. $W_A - 250$ mm), the estimated number of spring irrigations and the yield and net return at $W_A$.

<table>
<thead>
<tr>
<th>Water Applied</th>
<th>Total Irrig’n</th>
<th>Spring Irrig’n</th>
<th>Yield</th>
<th>Net Return</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(ML ha$^{-1}$)</td>
<td>(number)</td>
<td>(t ha$^{-1}$)</td>
</tr>
<tr>
<td>Wheat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_m$</td>
<td>920</td>
<td>6.7</td>
<td>7 to 9</td>
<td>8.3</td>
</tr>
<tr>
<td>$W_l$</td>
<td>708</td>
<td>4.6</td>
<td>5 to 7</td>
<td>7.8</td>
</tr>
<tr>
<td>$W_w$</td>
<td>561</td>
<td>3.1</td>
<td>2 to 4</td>
<td>6.7</td>
</tr>
<tr>
<td>Canola</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_m$</td>
<td>530</td>
<td>2.8</td>
<td>2 to 3</td>
<td>3.5</td>
</tr>
<tr>
<td>$W_l$</td>
<td>467</td>
<td>2.2</td>
<td>1 to 2</td>
<td>3.4</td>
</tr>
<tr>
<td>$W_w$</td>
<td>421</td>
<td>1.7</td>
<td>0 to 1</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Diminishing marginal returns ensure that irrigating to maximise yield is not a profit maximising strategy. Never-the-less, crop yields at $W_l$ are not much lower than at $W_m$, which indicates the price of water ($40.43$ ML$^{-1}$ in Singh, *et al.* 2007) is relatively cheap compared to the crop prices used in this analysis. This is particularly the case for the canola at $350$ t$^{-1}$, though the small difference in canola yield between $W_m$ and $W_l$ is also a reflection of the poor response to spring irrigation observed in this experiment. Wheat had a greater response to spring irrigation and it kept responding at greater $W_A$, which is why the profit maximising strategy when land is limiting is to apply 4.6 ML ha$^{-1}$ to wheat to achieve 8 t ha$^{-1}$. However, if water is non-limiting, the profit maximising strategy is more likely to be to irrigate rice in summer rather than to irrigate winter crops as rice has a net return of $1,000$ to $1,300$ ha$^{-1}$ (Whitworth, *et al.* 2002).

Prior to the introduction of the Cap on irrigation diversions in the MDB in 1995 (MDBC 1999), water may well have been non-limiting on many farms in the Murray Valley so the strategy to grow rice in summer and irrigate winter crops for high yield was appropriate. This is no longer the case and the profit maximising strategy when water is limiting is to spread the available allocation out over a larger area and maximise the average net return per ML (Yaron & Bresler 1983). From Table 5-2, it is clear that when irrigation water is limiting, profits will be maximised if available supplies are used to pre-irrigate canola and possibly give it one spring irrigation, as this will spread the water furthest and provide the highest net return per ML.
5.2 Estimating spring irrigation requirements

The preceding analysis is useful in showing the financial benefits to irrigators of spreading water out and deficit irrigating when water is limiting. However, the analysis does not show the most appropriate irrigation strategy from an agronomic standpoint as it does not consider the effect of the timing or severity of periods of water stress on crop growth. The single $K_c$ model of FAO 56 (Allen, et al. 1998) can be used to estimate the amount of water required to avoid crop water stress and maximise yield.

5.2.1 Crop growth stage lengths

Estimating the length of each crop growth stage is the first step in constructing a generalised $K_c$ curve for any crop. Whilst it has been commonly presumed in the southern MDB that crop growth stage lengths of wheat and canola are similar (Hughes 1999; Smith & Gibbs 1997; M. Edraki, 2001, pers. comm.), the results of this experiment show that this is not the case (Figure 4-23, page 96). The differences between the canola and the wheat in their patterns of development included:

- slower early canopy growth in the canola resulted in a longer initial stage. This is attributed to a strong vernalisation and photoperiod response in the canola between sowing to buds visible (Robertson, et al. 2002) which is evidenced by the similar rate of leaf area and biomass development across years in the canola when compared using Julian date (Figure 4-5 to Figure 4-8).

- Water stress during flowering caused the loss of green leaf in the canola (Bernadi 1996) and shortened the mid-season stage. The main effect of imposing a similar level of water stress in the wheat was to shorten the length of the late season stage (i.e. grain filling period). The different response of the two crops is attributed to the indeterminate nature of canola which permits leaf area and flowering to recover with the resumption of water supply during the vegetative and flowering stages (Tesfamarian 2004; Zhang, et al. 2004), whereas the duration of flowering is fixed in a determinate crop such as wheat.

- The total growing season of the canola was approximately one week shorter than that of the wheat in both years, though this difference may have been 2 weeks in 1998 if the leaf disease *Septoria* had not hastened maturity of the wheat in $W_{Full}$. 
Phenological development in the wheat and canola agreed closely with that predicted by the models of Stapper & Fischer (1990a) and Robertson, et al. (2002) respectively. Together with leaf area data from this experiment and evidence in the literature, these models were used to establish criteria for determining generalised stage lengths for wheat and canola in the southern MDB. These criteria (Table 5-3) were used to estimate growth stage lengths for Murray Valley crops for a range of sowing dates (Table 5-4).

Table 5-3. The criteria used to model the end of the initial (1), development (2), mid-season (3) and late season (4) stages for use in the single Kc model (Allen, et al. 1998) for estimating the crop water requirements of wheat and canola in the Murray Valley. The source of the information used to establish each criterion is also indicated.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Stage</th>
<th>Criteria</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>1</td>
<td>200°Cd (&gt;3°C) after sowing</td>
<td>GC = 10% at 150 to 200°Cd after sowing from Evers, et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>550°Cd (&gt;3°C) after sowing</td>
<td>This experiment and supported by data from Evers, et al. (2007) and Meyer, et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>DC65 + 10 days</td>
<td>DC65 estimated from Stapper &amp; Fischer’s (1990a) model for medium-late maturing wheat</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>DC65 + 850°Cd (&gt;3°C)</td>
<td>This experiment and data in Cooper (1980), Steiner, et al. (1985), Thompson &amp; Chase (1992)</td>
</tr>
<tr>
<td>Canola</td>
<td>1</td>
<td>SM 3.3 – 40 days</td>
<td>This experiment</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>SM 3.3</td>
<td>From Robertson, et al.’s (2002) model</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>SM 3.3 + 52 days</td>
<td>This experiment</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>278 – (0.67×JD)</td>
<td>From data presented in Taylor &amp; Smith (1992) JD is sowing date in Julian days (R² = 0.98)</td>
</tr>
</tbody>
</table>

Table 5-4. Estimated length (days) of the initial, development, mid and late season growth stages for spring wheat and canola sown on a range of dates at Deniliquin.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Sowing Date</th>
<th>Initial</th>
<th>Devel’t</th>
<th>Mid season</th>
<th>Late season</th>
<th>Total Season</th>
<th>Maturity Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>1 May</td>
<td>20</td>
<td>52</td>
<td>76</td>
<td>55</td>
<td>203</td>
<td>20 Nov</td>
</tr>
<tr>
<td></td>
<td>15 May</td>
<td>25</td>
<td>58</td>
<td>59</td>
<td>52</td>
<td>194</td>
<td>25 Nov</td>
</tr>
<tr>
<td></td>
<td>1 June</td>
<td>31</td>
<td>55</td>
<td>47</td>
<td>49</td>
<td>182</td>
<td>30 Nov</td>
</tr>
<tr>
<td></td>
<td>15 June</td>
<td>35</td>
<td>48</td>
<td>43</td>
<td>46</td>
<td>172</td>
<td>4 Dec</td>
</tr>
<tr>
<td>Canola</td>
<td>1 May</td>
<td>62</td>
<td>40</td>
<td>52</td>
<td>43</td>
<td>197</td>
<td>14 Nov</td>
</tr>
<tr>
<td></td>
<td>15 May</td>
<td>58</td>
<td>40</td>
<td>52</td>
<td>38</td>
<td>188</td>
<td>19 Nov</td>
</tr>
<tr>
<td></td>
<td>1 June</td>
<td>49</td>
<td>40</td>
<td>52</td>
<td>35</td>
<td>176</td>
<td>24 Nov</td>
</tr>
<tr>
<td></td>
<td>15 June</td>
<td>36</td>
<td>40</td>
<td>52</td>
<td>35</td>
<td>163</td>
<td>25 Nov</td>
</tr>
</tbody>
</table>
5.2.2 Crop factors

Initial season stage

The crop factors for the initial stage ($K_{c\ ini}$) were higher than values given in advisory publications (Smith & Gibbs 1997; Hughes 1999; Giblin & Lacy 2003) and, for wheat, by Meyer, et al. (1999). This is because the magnitude of $K_{c\ ini}$ varies according to the interval between wetting events, the amount of rain in the period, and $ET_o$ (Allen, et al. 1998). The plots were irrigated on 2nd June 1998 and this was followed by $\approx 10$ mm of rainfall every 10 days for the following month when average $ET_o$ was 1.3 mm day$^{-1}$. Figure 29 of Allen, et al. (1998) indicates that under these conditions $K_{c\ ini}$ is 0.7, which is the average value for the wheat during this period. The average value for the canola was slightly higher (i.e. 0.8) and this is attributed to greater $E_s$ in the canola because of its lower early leaf area and slower early growth. $K_{c\ ini}$ should be adjusted in the Murray Valley if $ET_o$ is low and rainfall is frequent in the late autumn, early winter period.

Mid-season stage

The mid-season crop factor ($K_{c\ mid}$) for wheat of 1.2 found in this study is slightly more than the value of 1.15 recommended by Allen, et al. (1998) but within the range of values found by Keefer (1977) and Cooper (1987). The $K_{c\ mid}$ of 1.15 found for canola was slightly lower than that for wheat but equivalent to the value recommended by Allen, et al. (1998) for irrigated canola crops with dense plant populations. Climatic conditions affect the value of $K_{c\ mid}$ and Allen, et al. (1998) recommend adjusting $K_{c\ mid}$ when minimum RH% differs from 45% and wind speed at 2 m differs from 2.0 m s$^{-1}$. In 1998 however, the average minimum RH% was 47% and 45% for the mid-season stages of the wheat and canola respectively and the average wind speed was 2.1 m s$^{-1}$. The $K_{c\ mid}$ values obtained in this study are therefore considered representative of standard conditions and comparable to $K_{c\ mid}$ values in Table 12 of Allen, et al. (1998).

There is evidence in the literature to indicate that $K_{c\ mid}$ for canola could potentially be higher than that for wheat. Daily transpiration rates have been shown to be higher in canola (Scott & Sudmeyer 1993) and the stomatal conductance to water vapour of canola leaves is 2 to 4 times greater than that of wheat leaves (Gollan, et al. 1986; Henson, et al. 1989; 1989; Jensen, et al. 1996; Jensen, et al. 1998). It is possible that the
$K_{c \text{ mid}}$ of 1.38 observed in the canola between the 23\textsuperscript{rd} and 31\textsuperscript{st} August in 1998 (Table 4-16 page 98) was due to higher $ET_c$ in the canola when conditions were favourable (i.e. low $ET_o$, wet soil and high soil conductivity). However, this was not lasting and $K_{c \text{ mid}}$ fell, possibly because the soil dried and $ET_o$ increased, or possibly because transpiration from pods started to dominate and pod stomatal conductance is similar to that of wheat leaves (Mogensen, \textit{et al.} 1997; Jensen, \textit{et al.} 1998). This is due to shading by petals, which causes canola total leaf area to decline rapidly after full flower (Mendham 1981).

**Late-season stage**

The crop factors given by Allen, \textit{et al.} (1998) for the late season stage ($K_{c \text{ end}}$) are 0.25 and 0.35 for wheat and canola respectively. Whilst these values fitted the data from this experiment very well, the lowest values actually measured in I\textsubscript{Full} were approximately 0.6 for both crops (Figure 4-23, page 96). This occurred because 56 mm of rain fell on the 11\textsuperscript{th} November shortly before PM in the I\textsubscript{Full} crops and resulted in the $\Delta S$ data for the very end of the late season stage being unusable. However, the I\textsubscript{0}, I\textsubscript{1} and I\textsubscript{Def} crops did senesce under dry conditions and their $K_c$ values at PM support the adoption of the Allen, \textit{et al.} (1998) $K_{c \text{ end}}$ values for wheat and canola crops in the Murray Valley. Allen, \textit{et al.} (1998) note that adjusting $K_{c \text{ end}}$ is not necessary when RH\% and wind speed differ from standard conditions if crops are allowed to senesce and dry in the field.

These $K_{c \text{ end}}$ values are lower than other values recommended for wheat and canola in the southern NSW. Meyer, \textit{et al.} (1999) determined a $K_{c \text{ end}}$ for wheat at Griffith of 0.4 using Penman-Meyer $ET_o$. This is nearly double the $K_{c \text{ end}}$ for wheat found in this study when they are compared as a proportion of their respective $K_{c \text{ mid}}$ values (i.e. 0.38 compared to 0.21). However, Meyer, \textit{et al.}'s (1999) data shows that $K_{c \text{ end}}$ of the three wheat crops they studied was 0.2 to 0.3 at the very end of the season, which is in line with $K_{c \text{ end}}$ from this experiment. As Penman-Meyer $ET_o$ is lower than Penman-Monteith $ET_o$, the $K_{c \text{ end}}$ values of 0.4 to 0.6 recommended in advisory publications (Smith & Gibbs 1997; Hughes 1999; Giblin & Lacy 2003) are not supported by this evidence.

**Calculation of $ET_o$**

Crop coefficients are specific to the method used to estimate $ET_o$ and in this study they were determined using Penman-Monteith $ET_o$ (see Appendix A). Whilst a National
Workshop in 2002 recommended the Penman-Monteith equation be adopted as a national standard for Australia (NPIRD 2002), a network of automatic weather stations supports the use of $K_c$ values based on the Penman-Meyer $ET_o$ equation in the irrigation districts of southern NSW. As a note of caution, there is the potential for considerable error in $ET_c$ if the $K_c$ values obtained in this study are used with locally available Penman-Meyer $ET_o$ without being adjusted.

### 5.2.3 Maximum spring irrigation requirements

The results show that when fully irrigated, wheat required more water than canola, with 24 and 56 mm more water applied to $W_{Full}$ than to $C_{Full}$ in 1998 and 1999 respectively. In line with Krogman & Hobbs’ (1975) findings, $C_{Full}$ needed one less irrigation than $W_{Full}$ because of its quicker maturity. This was not obvious in 1998 as the 56 mm of rain on 11th November fell too late to contribute to canola yield, yet it did replace a final irrigation in $W_{Full}$. The depths of water applied to $C_{Full}$ and $W_{Full}$ in 1998 (479 and 502 mm respectively) and 1999 (527 and 583 mm respectively) are in line with the reported water use of other fully irrigated wheat (Steiner, et al. 1985) and canola (Taylor, et al. 1991) crops in the irrigation districts of southern NSW and northern Victoria.

The FAO 56 guidelines for computing crop water requirements (Allen, et al. 1998) were used to model full irrigation of wheat and canola in the Murray Valley. Daily rain, $E_{pan}$, minimum RH% and wind speed at Deniliquin between 1960 and 2005 was obtained from the Bureau of Meteorology. Crop growth stage lengths (Table 5-4) and $K_c$ values were as determined by this study, with $K_{c\text{ ini}}$ and $K_{c\text{ mid}}$ adjusted for “non-standard” weather conditions using equations in Annex 7 and equation 62 respectively of Allen, et al. (1998). Sowing was modelled to occur after the first significant rain (i.e. >10 mm over 4 days) in the period between 26th April and 16th June. It was assumed that crops were pre-irrigated in mid-March and subsequent irrigations could only occur between 23rd August and two weeks before the end of the late season stage.

The single $K_c$ model was validated using the data from the wheat and canola in Site 1a in 1998 and a close correspondence was achieved between the actual and modelled timing of spring irrigations and actual and modelled $W_A$. Modelled $ET_c$ was within 15 mm of actual $ET_c$. The model predicted one less irrigation than actual, but this occurred because the final irrigation of $I_{Full}$ on the 5th Nov occurred within 2 weeks of harvest.
The model was run using two irrigation intervals: the first with a readily available water capacity (RAWC) of 55 mm (similar to the Birganbigi loam) and the second with a RAWC of 75 mm, which is typical of red-brown earths on the Riverine plain (Loveday, et al. 1978). Apart from 1976 when there was no rain for sowing, the results (Figure 5-4) show that, on average, the canola will require one less irrigation than wheat in the NSW Murray Valley if fully irrigated. Although the median number of irrigations required by both crops to avoid water stress in spring was 3 and 2 when RAWC was 55 and 75 mm respectively, the average number of irrigations was 2.8 and 2.1 for the canola compared to 3.4 and 2.6 for the wheat.

![Histograms showing spring irrigation requirements of wheat and canola](image)

**Figure 5-4.** Spring irrigation requirements of wheat and canola in the Murray Valley between 1960 and 2005, as predicted using the FAO 56 single \( K_c \) model (Allen, et al. 1998). These histograms show the frequency (as a % of all years) with which the indicated number of spring irrigations was predicted to be required during this period in order to avoid drought stress in the two crops in soils with a RAWC of 55 mm (left) and 75 mm (right).

The results (Figure 5-4) show that it is unlikely that wheat in the central Murray Valley will reach PM without encountering at least one period in spring when it will suffer water stress if not irrigated. By comparison, spring irrigation of canola was not required in 7% and 11% of years when RAWC was 55 and 75 mm respectively. This is attributed to the slight but cumulative effects of a shorter duration mid-season stage, a lower \( K_c \) mid and a quicker maturity in canola. Increasing the water holding capacity of the soil from 55 to 75 mm reduced the median number of irrigations required in spring from 3 to 2 and this resulted in a small (i.e. approximately 10 mm) decrease in \( W_A \) and \( DP \) for both crops. The model also showed that early sown crops require fewer spring irrigations than later sown crops, confirming Taylor & Smith’s (1992) findings from sowing date experiments with canola at Tatura, Vic.
5.3 Crop responses to spring irrigation

The patterns of phenological development and leaf area and dry matter accumulation in the fully irrigated crops in this experiment closely followed those reported for fully irrigated wheat and canola in trials on similar soils in the southern MDB. These trials include those of Cooper (1980a), Stapper & Fischer (1990b) and Thompson & Chase (1992) on wheat in the Murrumbidgee valley and of Taylor, et al. (1991) and Taylor & Smith (1992) on canola in northern Victoria.

Yields of the fully irrigated crops were typical of district “best practice” (Beecher, et al. 1995) but lower than some maximum yields reported elsewhere in the southern MDB. 7.3 t ha\(^{-1}\) from W\(_{\text{Full}}\) in Site 2 in 1999 was comparable to Thompson & Chase’s (1992) 7.0 t ha\(^{-1}\) for fully irrigated wheat and slightly better than the average yields of 6-7 t/ha\(^{-1}\) from a range of genotypes for May to July sowings reported by Stapper & Fischer (1990b). However, maximum yields of 7.8, 8.0 and 8.9 t ha\(^{-1}\) in the Murrumbidgee Valley reported by Steiner, et al. (1985), Cooper (1980a) and Stapper & Fischer (1990b) respectively show the potential for higher irrigated wheat yields on similar soils.

The difference between achieved and potential yield was greater in the canola. The maximum yield of 3.6 t ha\(^{-1}\) from C\(_{\text{Full}}\) in Site 2 in 1999 was similar to the 3.8 t ha\(^{-1}\) achieved by Wright, et al. (1988), but considerably lower than the maximum yields of 5.2 and 4.8 t ha\(^{-1}\) achieved by Taylor, et al. (1991) and Taylor & Smith (1992) respectively. This greater difference may be an artefact of the small area (2-3 m\(^{2}\)) sampled in the Victorian canola studies. By comparison, all the wheat studies except Steiner’s used plot harvesters to sample larger areas (≈ 25-35 m\(^{2}\)) for grain yield.

Reducing the amount of irrigation applied in spring shortened the post anthesis period in the wheat and reduced total biomass and spike numbers at PM, as well as harvest index, grain size and yield. This is consistent with the findings of Fischer & Kohn (1966), Cooper (1980a), Thompson & Chase (1992) and Steiner, et al. (1985) and fits with other reported responses of wheat to water stress during stem elongation, anthesis and/or grain-filling stages (McDonald, et al. 1984; Robertson & Guinta 1994).

In canola, the primary effect of reducing the amount of irrigation applied in spring was to hasten maturity and there was no significant effect on plant numbers, biomass or
harvest index. There was a significant yield difference between $C_0$ and $C_{Full}$ in both years but, compared to the wheat, the response to spring irrigation was poor. This was particularly highlighted by the non-significance of the relationship between spring applied water and canola grain yield (Section 4.13). These findings are consistent with grower experience in the district (Lacy & Thompson 1998) and they confirm previous studies which have found that canola yield is less sensitive to water stress and hence less responsive to irrigation than wheat (Munoz and Fernandez 1978; Morizet et al. 1984; Singh et al. 1989; Holland et al. 1999).

The difference in the response to spring irrigation of the two crops appears to be mainly due to the timing of the periods of water stress which occurred in the deficit irrigation treatments in 1998 and 1999. The effect of these dry periods on the final grain yield of each crop depended on the stage of growth during which they occurred, with the effect expressed through a reduction in the yield component that was being laid down at that time. Ranked in order of temporal determination, these yield components are: yield/m$^2 = $ spikes/m$^2 \times$ grains/spike $\times$ grain weight for wheat (Stapper & Fischer 1990); and yield/m$^2 = $ pods/m$^2 \times$ seeds/pod $\times$ seed weight for canola (Mendham, et al. 1984).

### 5.3.1 1998

In 1998, the first spring irrigation on the 8th September coincided with the late-boot stage in the wheat (DC47) and mid-flowering (SM4.5) in the canola. Water stress developed in the $I_0$ treatments following this but was alleviated on 21st–23rd September by 42 mm of rain. This rain started roughly 7 days prior to the start of anthesis in the wheat and 12 days prior to the end of flowering in the canola.

Meiosis in wheat coincides with the boot stage and is a critical stage of development because it originates the pollen and the embryo sac (Acevedo, et al. 2002). The $W_0$ plots were water stressed in mid-September, after the boot stage and before anthesis, so plants were not water stressed at either critical stage. Spike size was thus not affected and there was no significant difference in the number of grains per spike across the irrigation treatments. The fact that conditions for both $W_0$ and $W_1$ were similar following the September rain explains the similarity of the yields from these two treatments in 1998. For $C_0$, the water stress in September occurred during the critical three weeks after full flower (i.e. 7 days after 50% of plants had at least one flower open) when pod walls are
growing rapidly and seeds are likely to abort if plants are water stressed (Mendham, et al. 1981; Mendham, et al. 1984). Seeds per pod were not counted, but there was no significant difference in pods per plant or grain yield between C0 and C1 in 1998. This suggests there was time in the 12 days of flowering after the rain in September for C0 to compensate for any earlier pod/seed loss. Zhang, et al. (2004) observed a similar compensatory response (to waterlogging) which they attributed to the indeterminate nature of canola and Choudhury, et al. (1990) found that rain within a week of 50% flowering led to rainfed yields similar to those from canola irrigated at 50% flowering.

Water stress during grain filling is the primary cause of the significant yield reduction in the I0 and I1 treatments in 1998. In both crops, this late water stress shortened the duration of the grain filling period and reduced grain size and yields. Similar observations have been made by Thompson & Chase (1992) for wheat and by Mailer & Cornish (1987) and Taylor, et al. (1991) for canola. Kernel weights in W0 and W1 were less than 30 mg, indicating that some degree of “haying-off” occurred in the wheat in these treatments (van Herwaarden, et al. 1998). The fact that W0 extracted 20 mm more water from the profile by early November than W1 supports this and highlights the risk associated with creating a large anthesis biomass in wheat with the “1 spring irrigation” strategy (as applied in this experiment) if follow up rains do not occur.

Yields from IDef and IFull were similar in 1998. In the wheat, this is attributed to the effect of the leaf disease Septoria (see Section 5.4 below). In the canola, the rain in late September meant a similar amount of water was applied to the CDef and CFull crops up until early pod development. A number of studies have shown that biomass and leaf area at flowering sets canola yield potential because it determines the assimilate supply to developing seeds (Mendham, et al. 1981; Mendham, et al. 1984; Bernadi 1996). The (non-significant) difference in yield between CDef and CFull in 1998 is thus most likely a reflection of the differences in their biomass at flowering rather than any post-flowering difference in water stress. Richards & Thurling (1978) found that canola was relatively insensitive to drought during seed development and it is suggested that the water stress in CDef during October (indicated by the $\psi_p$ data) was not sufficient to affect grain size. The fourth and final irrigation of CFull thus appears to have had little effect on grain yield, indicating that the water productivity of canola may be improved by deficit irrigation during seed development.
5.3.2 1999

In 1999, harvest index and grain weight were not significantly affected by irrigation treatment in either of the two crops, indicating that the above average rainfall in October alleviated any water stress in the $I_0$, $I_1$ and $I_{Def}$ treatments during grain fill. Thus, the only period in which water stress affected grain yields in 1999 occurred after the first spring irrigation (18th September) and ended with the rain on 3rd October.

In the wheat, this dry period coincided with the period from ear emergence to the start of anthesis, so again water stress was avoided during meiosis and anthesis. There was a positive linear correlation ($R^2 = 0.96$) between spikes m$^{-2}$ and yield in 1999, indicating that the abortion of late-maturing tillers was the primary mechanism for the significant differences in wheat yields in 1999. A similar effect was observed by Cooper (1980a), McDonald, et al. (1984) and Thompson & Chase (1992). Tillers numbers were proportional to the amount of water applied in spring (i.e. $W_0 < W_1$ & $W_{Def} < W_{Full}$) and the similar yield of the $W_1$ and $W_{Def}$ treatments is attributed to the October rain which negated the effect of the second spring irrigation (87 mm) of the $W_{Def}$ treatment.

In the canola, peak flowering (on 14th September) occurred four days prior to the first spring irrigation and conditions remained dry until flowering was mostly finished. The rain on the 3rd October occurred after flowering had ceased, so stressed plants were not able to compensate for any earlier loss of seeds or pods and a significant difference developed between $C_0$ and the other treatments. The rain in October ensured favourable conditions during seed development so all four treatments had similar grain weights and significant differences between $C_1$, $C_{Def}$ and $C_{Full}$ did not eventuate. Taylor, et al. (1991) found that canola seed size was decreased by severe water stress (PAW < 50%) during seed development, so the similarity of the grain weights suggests that the level of water stress in $C_0$, $C_1$ and $C_{Def}$ was not severe enough to affect grain filling. This supports the finding in 1998 that moderate stress during seed development has little effect on canola seed size. There was a positive linear correlation ($R^2 = 0.53$, $P < 0.01$) between individual plot biomass at flowering and canola grain yield in 1999 and the difference in the yields from $C_1$, $C_{Def}$ and $C_{Full}$ is considered to be due to non-treatment differences in the amount of biomass accumulated prior to flowering.
5.4 Factors limiting to high yields

5.4.1 Disease

The similarity of the yields from the WDef and WFull treatments in 1998 is attributed to disease (Septoria). This particularly affected the WFull treatment late in the season, causing a loss of green leaf and shortening the grain filling period by 5 to 9 days when compared to the WFull treatments in 1999 (Figure 4-8). Accelerated senescence shortens the linear phase of grain growth and the loss of green leaf reduces the amount of pre-anthesis assimilate that is re-translocated to grain (van Herwaarden, et al. 1998; Panozzo & Eagles 1999; Acevedo, et al. 2002). This reduces grain weight and yield in direct proportion to the decrease in post anthesis leaf area duration (Fischer & Kohn 1966). The magnitude of the yield loss caused by the Septoria is indicated by the 0.75 t ha$^{-1}$ difference in yield from the fully irrigated wheat at Site 1 between 1998 and 1999.

5.4.2 Temperature

Wheat

Temperatures > 30°C during floret formation cause complete sterility in wheat (Owen 1971; Saini & Aspinal 1982) and high temperatures during grain filling depress yields (McDonald, et al. 1983; 1984), with kernel weights being reduced by 5% per 1°C rise above 14°C in average temperature during grain filling (Stapper & Fischer 1990c). In this experiment, anthesis occurred during the first week of October in 1998 and 1999 so temperature was not expected to have affected yields as this was within the optimum time for anthesis in southern NSW (Stapper & Fischer 1990c). However, average temperatures during grain filling were higher than 14°C, being 15.5°C and 16.9°C in 1998 and 1999 respectively. Stapper & Fischer’s (1990c) model indicates that the seed weight in the WFull treatment in 1998 should have been roughly 45 mg, rather than the actual 33 mg, and this discrepancy is attributed to the leaf loss and premature senescence caused by the Septoria. By contrast, seed weights in 1999 fitted Stapper & Fischer’s model and it is possible that yields may have been up to 15% greater if average temperatures during grain filling had been 3°C lower.
Canola

High temperatures are known to affect canola oil content (e.g. Canvin 1965; Si, et al. 2003) and a negative relationship between temperature during flowering and grain filling and yield has been observed (Beech & Norman 1964). Morrison, et al. (1989) found that *B. napus* is most sensitive to high temperature from late bud development to early seed development and, in the field, yields of *B. napus* are reduced when temperatures during flowering exceed 29.5°C, primarily because the number of flowers and the number and size of the seeds per flower are reduced (Morrison & Stewart 2002).

In this experiment, there was no inter-year difference in the level of heat stress during flowering (as defined by Morrison & Stewart), as maximum daily temperatures during flowering never exceeded 29.5°C in either year. However, there were 6 days in 1998 (when yields were lower) but only 1 in 1999 when the daily temperature exceeded 29.5°C during seed/pod development. This suggests that high temperatures in the post-flowering period, rather than during flowering, may have played a part in limiting canola yields (at least in 1998).

![Graph showing the relationship between seed yield and average daily mean temperature during pod and seed development in fully irrigated *B. napus* crops](image)

Figure 5-5. The relationship between seed yield and average daily mean temperature during pod and seed development in fully irrigated *B. napus* crops (☐ Mendham et al. (1984), ● Wright, et al. (1988), ◊ Taylor, et al. (1991), ▲ Bernadi (1996), ○ Jensen, et al. (1996) and △ this experiment).

Davidson & Downes (1976) found *B. napus* yields fell from 20 g/plant at 15/10°C to zero at 30/25 °C in a growth chamber; that high temperature after flowering swamped all other temperature effects; and that mean temperatures > 12°C during seed development caused marked reductions in yield. These findings are supported by data
pooled from irrigated canola experiments in Tasmania (Mendham, et al. 1984), northern Victoria (Wright, et al. 1988; Taylor, et al. 1991), southern NSW (this experiment), central NSW (Bernadi 1996) and Denmark (Jensen, et al. 1996). The results (Figure 5-5) indicate that canola seed yield declines by 0.7 t ha\(^{-1}\) with each 1°C rise in the mean daily temperature above 13°C during seed/pod development, which is similar to the effect observed by Davidson & Downes (1976) for a plant density of 50-55 plants m\(^2\).

Robertson, et al. (2002) presumed that temperatures between 20°C and 30°C are not a relevant issue for canola, as “mean temperatures greater than 20°C will be rarely encountered in most canola-growing environments.” However, this ignores the effect of short periods of high temperature, such as were experienced in 1998 when there were 6 days of > 29.5°C during seed/pod development. It is felt that this was a factor in causing the lower canola yields that year. This is supported by Aksouh, et al. (2001), who showed that yields of the cultivars Oscar, Monty and Range were reduced when plants were subjected to a 5 day heat shock during seed development (though Oscar was not affected when heat stress was imposed more gradually).

Because there are on average 3.6 days in October when maximum daily temperatures at Deniliquin exceed 30°C (Clewett, et al. 1999), heat shock may be a significant yield limiting factor for canola in the NSW Murray Valley. Furthermore, average daily temperature at Deniliquin in October is 16°C (Clewett, et al. 1999) and the data presented in Figure 5-5 indicates that this will limit maximum achievable yields to approximately 3.5 t ha\(^{-1}\). There thus appears reasonable evidence to indicate that high temperatures during seed/pod development (either gradually or suddenly imposed) may limit canola yields in the NSW Murray Valley and it is suggested that the effect of these high temperatures requires further investigation.

### 5.4.3 Soil type

Particle size analysis (Table 3-1 and Table 3-2) and observations during installation of the NMM access tubes showed the Cobram loam (Site 2) was lighter in texture than the Birganbigil loam (Site 1). As well as this difference in texture, the Birganbigil loam has a sodic B horizon which has poor structure, low stability and a large ped size, all of which is known to lead to low saturated hydraulic conductivity (Loveday, et al. 1978; Greacen & Williams 1983). Micro-pores (< 30 µm diameter) predominate in the B
horizon of this soil type and these small pores impose a high resistance to flow, reducing the bulk velocity of water flow for a given potential gradient and limiting the available water range (Olsson & Rose 1978).

The Birganbigil loam is also a slightly shrink/swell soil (Jayawardane & Greacen 1987) and it cracks upon drying. Average penetration resistance of the B horizon is greater than the commonly used critical threshold for root growth of 2000 kPa (Da Silva & Kay; Hanza & Anderson – in Chan 2006) when the soil is drier than 0.32 m m$^{-1}$ (S. North, unpublished data), so roots grow preferentially in these soil cracks and macropores (Meyer & Barrs 1991; Passioura 1991). This results in a “clumped” root distribution which may increase the extent of the root system but does slow the rate at which roots can extract water from the soil between the macropores (Passioura 1991; Wang & Smith 2004) because the resistance to water flow through soil to clumped roots is up to two orders of magnitude higher than if roots are uniformly arranged (Tardieu, et al. 1992).

Inter-site differences

Despite being similarly irrigated and fertilised and having similar early season plant populations, the yields of the fully irrigated crops in Site 2 were 110% and 120-130% of those in Site 1b in 1999 for the wheat and canola respectively. High resistance to water flow in the B horizon of the Birganbigil loam is considered to have restricted the rate of water movement from the soil to the roots at Site 1b and reduced transpiration below potential rates when evaporative demand increased in spring.

Denmead & Shaw (1962) found transpiration in corn grown in pots of silty clay loam fell below the potential rate when average root zone soil suction was only 30-40 kPa when potential transpiration was 5-6 mm day$^{-1}$. Jensen, et al. (1996) observed that yields of *B. napus* crops were not affected when evaporative demand was low (2-4 mm day$^{-1}$), but higher evaporative demand (4-5 mm day$^{-1}$) caused greater water stress and lowered yields, even though the soil dried to a similar extent.

In 1999, $ET_o$ exceeded 5 mm day$^{-1}$ for 7 days in October and 16 in November. Furthermore, irrigating at an $E-P$ deficit of 60 mm is roughly equivalent to irrigating when soil matric potential at 30 cm in the Birganbigil loam is 60 kPa (North 2004). It is therefore considered likely that there were periods in spring 1999 when transpiration by the crops in Site 1b was reduced below potential rates and some degree of water stress
particularly at mid-day) was experienced. Evidence of this is seen in the lower rates of biomass accumulation in the Site 1b crops from early October 1999 onwards (Figure 4-7 and Figure 4-8) when compared to the Site 2 crops, as well as in the smaller grain weight of the Site 1b crops (Table 4-7). The number of canola stems m\(^{-2}\) in Site 1b also declined following anthesis in 1999, whereas canola stem density in Site 2 remained steady during the same period (Figure 4-3). Water stress also decreases both the number and the growth rate of branches in an indeterminate plant (Taiz & Zeiger 1991) and this is seen as further evidence of water stress in the canola induced by high evaporative demand and high soil resistance to water flow in the Birganbigil loam at Site 1.

Inter-crop differences

The threshold dawn plant water potential (\(\psi_p\)) below which growth rates and yields are reduced, is reported to be -0.4 MPa for both wheat (Meyer & Green 1980) and canola (Bernadi 1996). This has been confirmed by observations of dawn \(\psi_p\) greater than -0.4 MPa in fully irrigated and non-water stressed wheat (McDonald, et al. 1984; Liang, et al. 2002) and greater than -0.35 MPa in non-senescent canola when soil matric potential was maintained above -30 kPa (Jensen, et al. 1998).

There was a significant effect of crop type on \(\psi_p\) in spring 1998, with \(\psi_p\) in the canola being significantly lower than \(\psi_p\) in the wheat at all times after the 30\(^{th}\) September. It therefore appears that the canola experienced a greater degree of water stress than the wheat during spring at all levels of irrigation on the Birganbigil loam. The \(\psi_p\) data also shows that the canola in C\(_{\text{Full}}\) was water stressed (i.e. \(\psi_p < -0.4\) MPa) prior to it being irrigated on the 10\(^{th}\) October, as well as on the 30\(^{th}\) Sept and 15\(^{th}\) Oct. Dawn \(\psi_p\) of the wheat in W\(_{\text{Full}}\) was greater than the -0.4 MPa threshold at all three of these times.

When designing this experiment, it was assumed that Full irrigation at an \(E\)-\(P\) deficit of 60 mm would ensure that neither the wheat nor the canola would become water stressed. The lack of a significant difference in \(S\) (0-1.0 m) between C\(_{\text{Full}}\) and W\(_{\text{Full}}\) appears to justify this assumption. However, the \(\psi_p\) data indicates that the canola on the Birganbigil loam was water stressed at least three times in spring 1998 whereas the wheat was not, which suggests the optimal irrigation interval for canola should be shorter than that for wheat: e.g. an \(E\)-\(P\) deficit of 50 mm as in the Victorian studies of Wright, et al. (1988) and Taylor, et al. (1991). However, dawn \(\psi_p\) of the fully irrigated canola was less than...
the -0.4 MPa threshold on the 30th September (Table 4-8) and 15th October (Table 4-9) when only 36% and 27% respectively of plant available water had been used and the \( E-P \) deficit was 23 and 13 mm. Shortening the irrigation interval for the canola is therefore not likely to have overcome this stress but may have led to waterlogging.

It is suggested that the low hydraulic conductivity in the B horizon of the Birganbigil loam had a greater effect on canola yield than it did on wheat yield and that the \( \psi_p \) data is an indicator of this. On the Cobram loam, the maximum yield in both the wheat and the canola was 120% of the minimum. On the Birganbigil loam in 1998, on the other hand, the maximum canola yield was 110% of the minimum yield whilst the maximum wheat yield was at least 130% of the minimum (and possibly more given the effect of the \( \textit{Septoria} \)). Furthermore, in 1999, the yield from \( \text{C}_{\text{Full}} \) was 40% of the yield from \( \text{W}_{\text{Full}} \) on the Birganbigil loam, whereas on the Cobram loam it was 50%.

The canola therefore had a proportionately lower response to irrigation than the wheat when grown on the Birganbigil loam. It is considered that this was due to a lower plant resistance to water flow in the canola which, when combined with the high resistance to water flow in the Birganbigil loam, resulted in the canola extracting water at a faster rate than the soil could supply when evaporative demand increased in spring. The result was that the canola on the Birganbigil loam became water stressed, a fact confirmed by the lower \( \psi_p \) and the reduced response to irrigation observed in the canola.

Plant resistances to water flow are lower and rates of water uptake per unit root length have been shown to greater in dicotyledonous compared to monocotyledonous species (Mason, et al. 1983; Hodgson & Chan 1984; Hamblin & Tennant 1987; Gregory & Brown 1989; Gallardo, et al. 1996). Whilst no direct evidence could be found to show that this is the case for canola, there is some indirect evidence. Morillon & Lassalles (2002) showed that spring wheat has the ability increase root resistance to water flow in response to drought whereas canola does not. The difference in \( \psi_p \) between leaves and upper stems in canola measured by Bernadi (1996 & 2000) was one sixth of the difference in \( \psi_p \) between the flag leaf and stem in wheat by measured by Frank & Harris (1973), indicating lower resistance to flow in canola xylem. Additionally, the stomatal conductance reported by Jensen, et al. (1996 & 1998) for non water stressed canola leaves and stems is at least twice and up to four times that of leaves of non-water stressed wheat reported by Gollan, et al. (1986) and Henson, et al. (1989 & 1989).
Dawn $\psi_p$ is in equilibrium with the water potential of the soil around active roots (Richter 1997; Ameglio, et al. 1998; Donovan, et al. 2003; Jones 2004). The lower dawn $\psi_p$ in the canola indicates that the soil around its roots was drier than the soil around the wheat roots. However, the $\theta_v$ data shows that the bulk soil in the surface and B horizon in late September and early October was drier under the wheat. For this to be the case, the volume of soil exploited by the canola roots in these horizons must have been smaller than the volume of soil exploited by the wheat roots. This implies either a lower root length density or a more clumped root distribution (or both) in the canola in the surface and B horizons of the Birganbigil loam. This conclusion is supported by the $\theta_v$ data, which shows that the wheat was able to extract significantly more water than the canola from the B horizon in the deficit irrigated treatments.

It is suggested that this difference arose because canola has a lower ability to penetrate hard soil peds between cracks in soils such as the B horizon of the Birganbigil loam. This is supported by Whiteley & Dexter (1984), who showed that 85% of wheat seminal roots were able to penetrate soil with a penetrometer resistance of 2 MPa after crossing a 1 mm wide crack whereas only 60% of canola seminal roots were able to do so. This finding is confirmed in field experiments by Chan, et al. (2006). The effect on canola yield of its lower ability to grow roots in hard soil is likely to be exacerbated by a feed-forward mechanism if plant resistances to water flow are indeed lower in canola.

Plant roots elongate when the turgor pressure inside new cells is sufficient to overcome the constraint of the cell walls and the external constraint imposed by the surrounding soil (Klepper 1990; Materechera, et al. 1991; Wang & Smith 2004). More rapid water extraction from the soil surrounding the canola roots would have increased soil resistance to flow to the roots. A lower ability to penetrate peds would have limited root length density and produced a clustered root distribution, further increasing soil resistance to water flow. As evaporative demand increased in spring, the ability of the soil to supply water to the canola at a rate sufficient to keep it hydrated would have fallen. Once turgor pressure fell, the pressure available within the root to overcome soil impedance and elongate would also have fallen. Mid-day wilting was observed in the canola in 1998 and this diurnal loss of turgor pressure would have further restricted the ability of the canola roots to elongate in the hard soil of the Birganbigil loam.
From full flower on, however, canola loses leaves because of shading from petals and transpiration becomes dominated by ripening pods. The canola therefore becomes more drought-resistant because the pods are succulent, have a low specific area, and stomatal conductance is low (Mogensen, et al. 1997). The recommended irrigation strategy for canola is thus to ensure sufficient moisture to maximise biomass at flowering and to avoid water stress until 3 weeks after full flower (Mendham 1981). This will maximise leaf area and carbohydrate assimilation prior to the onset of high evaporative demand and provide a large “source” for developing seeds. After this time, canola should be deficit irrigated because its indeterminate nature provides it with a greater ability to make use of rains post flowering than determinate wheat.

5.5 Potential benefits of crops after rice

Rice is the single most important summer crop grown in the irrigation districts of southern NSW but it results in very wet sub-soils after it has been harvested in autumn. It has been shown that if soil moisture content is high in autumn, then winter rainfall can contribute significantly to groundwater recharge in these districts in wet years (van der Lelij 1989). Humphreys, et al. (2001) showed that DP during the winter/spring period can be reduced by growing wheat after rice and that using this water to grow a crop is an effective way for irrigators to increase their water productivity (WP).

The tensiometer and water balance data in this experiment show that canola used approximately 20-30 mm more water than the wheat in all treatments except I_{Full}. The main reason for this difference was the greater ability of the canola to extract deep soil moisture (Sections 4.9 and 4.10) which resulted in lower DP and greater CR under the canola in all irrigation treatments. This provides clear evidence that canola has a greater capacity to utilise water from deeper soil layers than wheat. It confirms statements to this effect that were either unsupported (Weiss 1983; Colton & Sykes 1992; Ryan et al. 2003) or based on greater observed rooting depth (Holland et al. 1999).

Exactly why canola is able to extract more water from deeper in the soil than wheat is unclear. There are numerous studies to show that wheat roots are able to grow and extract water to 120 cm (e.g. Gregory, et al. 1978; Hamblin & Tennant 1987; Meyer & Barrs 1991). The lower leaf water potential in the canola would have ensured a greater
potential difference between water in the bulk soil and the xylem and this may have allowed the canola to extract water from the soil to a lower potential than the wheat. However, it is also likely that the root distributions of the two crops were different. The $\theta_v$ data and the patterns of moisture extraction indicate that the wheat roots were more active in the top 60 cm of the profile, whereas the canola appeared able to get more roots to depth so that it was extracting water at 120 cm by the end of the season in $I_0$.

There is evidence to show that wheat roots tend to be shallower and have lower root length density at depth than canola (Kirkegaard, et al. 1997; Gregory 2006). However, it is possible that sub-soil constraints limited the growth of wheat roots below 80-100 cm in the Birganbigil loam, particularly given the high Cl$^{-}$ and ESP at 90-100 cm (Table 3-1). Soil water extraction was stopped in a Vertisol by a soil Cl$^{-}$ concentration content equal to that measured at 90-100 cm in the Birganbigil loam (Dang, et al. 2006a). Furthermore, Dang, et al. (2006b) observed no difference in depth of water extraction (1.2 – 1.3 m) by wheat and canola in a Vertisol when subsoil constraints (pH, EC, Cl$^{-}$ and ESP) were classified as low to medium but, on high constraint sites, the mean maximum depth of water extraction was 0.85 m for wheat and 1.0 m for canola.

There was no evidence that the canola extracted more water from depth than the wheat in the Cobram loam in 1999. In fact, neither crop in $I_0$ or $I_{full}$ appeared to use any water below approximately 60 cm (Figure 4-14). This is attributed to the more favourable soil conditions in the (non-rice suitable) Cobram loam and the more frequent rainfall in spring 1999. It is suggested that further work is required on a range of rice soils to confirm the results obtained from the Birganbigil loam. If canola is indeed better able to de-water soil profiles following rice, then this would fit well with the profit maximising strategy for canola as the rice water would replace the autumn pre-irrigation and canola’s lower water requirement would lessen the need to irrigate in spring, allowing water to be used elsewhere. To realise this potential, further work is needed to determine the best sowing practices to ensure establishment of canola following rice.

It was also shown that more water was removed from the soil profile when crops were deficit irrigated in spring, irrespective of crop type.
Chapter 6. Conclusions

The responses of wheat and canola to irrigation are very different; with wheat having a three-fold greater response to spring irrigation than canola. This difference arises principally because of differences in the nature of their growth and in the determinacy of the two crops. Wheat is determinate and it lays down yield components in the order plants/m$^2$, spikes/m$^2$, grains/spike and then grain weight and it does so sequentially. Any setback to the crop during a particular stage of growth when one of these components is being laid down reduces the yield potential of the crop. There is some ability to compensate if conditions improve, but this is limited and favourable conditions for growth are needed during each stage of development to ensure there is a continuing yield response up to the potential yield.

This response is reflected in the shape of the production function for wheat, which shows that yields increase with increasing applied water over a wide range up to a (current) potential yield of approximately 8 t ha$^{-1}$. The greater sensitivity of wheat to water stress, together with the assured response to irrigation, means that the profit maximising irrigation strategy for wheat should be to apply 3 to 4 spring irrigations to attain a target yield of 6-7 t ha$^{-1}$. Applying less water is highly likely to result in the crop experiencing a level of water stress and this stress will reduce $ returns by more than the cost saving achieved given that the bulk of the cost of production are incurred upfront in sowing and crop establishment. The strategy of applying one spring irrigation to wheat is not recommended because it has the potential to create a large biomass which will not be supported if follow up rains are not received.

Farm profitability will be improved by shifting along the production curve to the profit maximising point, rather than improving WP per se. Given that average district yields for irrigated wheat are around 3 to 4 t ha$^{-1}$, that yields of 8 t ha$^{-1}$ are achievable with good management, and that the difference in the costs of production between a 3-4 t ha$^{-1}$ crop and an 6-7 t ha$^{-1}$ crop is not large, then the best strategy with wheat is to minimise any limitations to higher yields (e.g. disease, high temperature) and apply water to obtain the recommended 6-7 t ha$^{-1}$. For growers already achieving yields of 6-7 t ha$^{-1}$, net returns will not be improved by applying more water to lift yields, particularly given
that water is now the limiting resource. Rather, their efforts may best be expended in improving their production function by upgrading their irrigation infrastructure to reduce losses which, for flood irrigation, are principally deep drainage.

In contrast to the wheat, canola is indeterminate and its yield components are laid down in the order plants/m², branches/plant pods/m², seeds/pod and seed weight. Unlike wheat, canola growth stages overlap so the plant has an ability to compensate after a period of (water) stress because there are yield components still coming on that will continue to grow and replace those lost once conditions improve. This capacity to resume vegetative and reproductive growth following relief from water stress appears to be one characteristic that contributes to the lack of response to water stress/irrigation. A second characteristic contributing to canola’s lack of response to irrigation is the development of drought resistance after flowering as pod area increases.

A third characteristic considered to have limited canola yields in this experiment is postulated. This is considered to have arisen as a result of high evaporative demand in spring, low soil hydraulic conductivity and restricted rooting in the B horizon of the Birganbigil loam, all of which combined to induce water stress. The effect of this water stress would have been exacerbated by high temperatures if transpiration was reduced to the point where plants were unable to remain cool. Results are presented to show that canola seed yield declines by 0.7 t ha⁻¹ with each 1°C rise in the mean daily temperature above 13°C during seed/pod development.

These characteristics of canola’s response to water are also reflected in the production function. The slow early crop growth and long time to ground cover means canola has a higher initial water requirement. Its sensitivity to water stress during the vegetative and flowering stages results in the good response to applied water between 200 and 350 mm and the three characteristics previously mentioned result in the yield plateau after 450 mm of applied water. It is considered that the first two of these three characteristics are compensatory in that they ensure yields are maintained if adverse conditions for growth are only transient. The third characteristic, however, is considered yield limiting because a given combination of soil type and climate will dictate the level of water stress experienced by canola in spring. Further work is required to test the hypothesis that this yield limiting characteristic is a consequence of low internal resistance to water flow in canola together with a lesser ability to penetrate hard soil.
The yield \((Y)\) and applied water \((W_A)\) production functions are considered representative of flood irrigated wheat and canola crops growing on red-brown earth and transitional red-brown earth soils in the southern Murray Darling Basin.

For wheat: \[ Y = -2.25 + 2.30 \times 10^{-2} \cdot W_A - 1.25 \times 10^{-5} \cdot W_A^2 \] \(R^2 = 0.938\).

For canola: \[ Y = -3.40 + 2.59 \times 10^{-2} \cdot W_A - 2.44 \times 10^{-5} \cdot W_A^2 \] \(R^2 = 0.915\).

Given that water is the limiting resource in the irrigation districts of the southern Murray Darling Basin, the profit maximising irrigation strategy for wheat is to pre-irrigate in autumn and apply 3-4 spring irrigations to attain a target yield of 6-7 t ha\(^{-1}\). For canola, the profit maximising strategy is to pre-irrigate in autumn and apply one spring irrigation to attain a target yield of 3.2 t ha\(^{-1}\).

\(K_{c,mid}\) for wheat and canola crops in the NSW Central Murray was determined to be 1.2 and 1.15 respectively. Existing crop phenology models adequately predicted the timing of key growth stages in both crops and this made it possible to determine generalised \(K_c\) curves for wheat and canola crops in the NSW central Murray Valley.

The \(K_c\) and crop stage data allowed maximum crop water requirements to be modelled for each crop over the period 1960 to 2005. The model results showed that, to avoid water stress in the spring period, canola requires one less irrigation on average than wheat in the NSW Murray Valley. For two soils with readily available water capacities (RAWC) of 55 mm and 75 mm, the modelled average number of irrigations required was 2.8 and 2.1 respectively for the canola and 3.4 and 2.6 respectively for the wheat.

When water is limiting, profits will be maximised if available supplies are spread out over as large an area as possible to maximise the average net return per ML. Canola was found to have the lowest water requirement, so profits may be maximised if available water supplies are allocated to canola. However, its poor response to irrigation makes this an economically risky strategy. To reduce this risk and ensure a sufficient response to spring irrigation, the following practices are recommended:

1. sow early - to avoid high temperatures later in spring and to reduce the number of irrigations required;
2. grow irrigated canola on better soil types – hard soils restrict root growth and water supply to the crop. High evaporative demand and high temperatures in
spring combine to limit canola’s yield potential on poor soils. An economically justifiable yield response to spring irrigation is more likely if canola is grown on more friable, less dense soils which have greater conductivity and water holding capacity.

Irrigating to maximise yield was very clearly not a profit maximising strategy.

For both crops, decreasing the number of spring irrigations decreased the amount of water left in the soil profile at maturity and reduced the amount of water lost as deep drainage. Fully irrigating either crop resulted in significant deep drainage, as did irrigating at an $E-P$ deficit of 90 mm. Conversely, it was very clear that deep drainage will only be avoided if crops are left unirrigated in spring. However, the canola was clearly better able to extract more water from deeper in the soil profile than wheat and the $C_1$ treatment was the only irrigation treatment that did not contribute to deep drainage. These findings, together with the evidence of canola’s lower requirement for and poorer response to spring irrigation (compared to wheat), suggest that the most profitable strategy for canola in the irrigation districts of the Murray Valley may be to grow it after rice to de-water soil profiles. This is consistent with the recommendations made above because, in this case, the canola would not be spring irrigated. Further work is required to show whether this is agronomically feasible and whether the results from this study are applicable to a wider range of rice-suitable soils.
Appendix A. Calculation of $K_p$ for BoM’s Class A pan at Deniliquin

A nearly continuous record of Class A pan evaporation was collected by the Bureau of Meteorology (BoM) at their Deniliquin site from mid-December 1977 to June 2003. In contrast to this, the data available for calculating $ET_o$ over the same period is neither extensive nor complete. The length and quality of the pan evaporation record warrants its use when examining the historical record at Deniliquin.

It has been commonly accepted that the pan coefficient for the BoM Class A pan at Deniliquin is 0.8 (Grieve, et al. 1986). However, this pan had a bird cover and the effect of this on $E_{pan}$ was not known. Allen, et al. (1998) recommend local calibration of $E_{pan}$ against $ET_o$ computed with the Penman-Monteith equation. This section describes such a calibration for the BoM Class A pan at Deniliquin. Data missing from the BoM record was estimated from data collected by the automatic weather station (AWS) at the Murray Valley Field Station (MVFS), approximately 15 km north of the BoM site.

A.1 Check on weather data used to calculate daily $ET_o$

A.1.1 Temperature

Maximum temperature in the 24 hours after 9 am and minimum temperature in the 24 hours before 9 am was available from the BoM. The data was recorded manually and is rated by the BoM as “quality controlled and acceptable”.

Maximum and minimum temperatures were available from NSW DPI’s AWS for the period 1998 to 2003. Comparison of this data with maximum and minimum temperatures from the BoM station (Figure A-1, Figure A-2 and Table A-1) showed there was a close correlation between the two stations and it was concluded that “patching” missing data in the BoM record with data from the AWS was appropriate.
Table A-1. Results of paired-t test and linear regression analysis comparing maximum and minimum temperatures from the Bureau of Meteorology’s Deniliquin station with those from the automatic weather station (AWS) at the Murray Valley Field Station

<table>
<thead>
<tr>
<th>Variable</th>
<th>Paired t test</th>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t$ value</td>
<td>$P$</td>
</tr>
<tr>
<td>Maximum Temp</td>
<td>9.38</td>
<td>$&lt; 0.0001$</td>
</tr>
<tr>
<td>Minimum Temp</td>
<td>21.17</td>
<td>$&lt; 0.0001$</td>
</tr>
</tbody>
</table>

Figure A-1. Comparison of maximum temperature in the 24 hours after 9 a.m. from the Bureau of Meteorology’s Deniliquin station with maximum daily temperature (midnight to midnight) from the automatic weather station located at the Murray Valley Field Station, Deniliquin.

Figure A-2. Comparison of minimum temperature in the 24 hours before 9 a.m. from the Bureau of Meteorology’s Deniliquin station with minimum daily temperature (midnight to midnight) from the automatic weather station located at the Murray Valley Field Station, Deniliquin.
A.1.2 Relative Humidity

Daily maximum and minimum relative humidity ($RH$) was not available from the BoM station. However, $RH$ at 0900 and 1500 hours was available and this was used instead. This data was manually recorded and is rated as “quality controlled and acceptable”.

A.1.3 Wind Run

Daily wind run data was not available from the BoM station. Wind run data was collected at the AWS with a good quality anemometer (DISS model WS100) mounted at a height of 2 m. The record is mostly complete, with data available from 1998 onwards. The daily wind run from the AWS was used in the calculation of $ET_o$.

A.1.4 Solar Radiation

Global Solar Exposure at Deniliquin was available from the BoM. This data was not recorded at the site, but was derived from satellite imagery processed by the BoM for the co-ordinates at which the station is located. The record is not complete, so solar radiation from the AWS was used to augment the BoM record. Regression analysis showed a strong correlation between the two data sets ($R^2 = 0.96$) but the AWS pyranometer had a response 90% of that measured by the BoM satellite (Figure A-3).

![Figure A-3. Relationship between daily solar radiation from NSW Agriculture’s automatic weather station and daily Global Solar Exposure at Deniliquin recorded on the same day by the Bureau of Meteorology’s satellite. The line of best fit has the form: $Rs_{AWS} = (0.89 \times Rs_{BoM}) - 0.64$ ($R^2 = 0.96$).](image-url)
Variation from a 1:1 line was expected as the spectral response of the AWS pyranometer (Environdata model SR10) does not cover the full solar spectrum. The inverse equation of the line of best fit to this data was used to estimate Global Solar Exposure on days when radiation data from the BoM satellite was missing.

A.2 Calculation of the pan coefficient ($K_p$) for Deniliquin

Weather data collected between 29th January 1998 and 22nd May 2003 was used to determine the pan coefficient ($K_p$). Allen, et al. (1998) recommend that $E_{pan}$ should only be used to predict $ET_o$ over periods of 10 days or longer, so 11 day running means of $ET_o$ and $E_{pan}$ were calculated. Over the period examined, there were 218 missing days of data.

$E_{pan}$ was recorded at 9 am for the previous 24 hour period. To account for this, the pan evaporation record was moved back one day (i.e. $E_{pan}$ recorded on the 24th applies to evaporation which occurred primarily on the 23rd). All other data related to the day on which it was recorded.

$ET_o$ was calculated using the example MicroSoft™ Excel spreadsheet from the “FAO Irrigation & Drainage Paper No 56” website\(^1\) (Allen 1999). This was adapted for calculating $ET_o$ at Deniliquin using the weather data set. Eleven day mean $ET_o$ was plotted against 11 day mean $E_{pan}$ and linear regression in SigmaPlot™ was used to find the line of best fit passing through the origin. The result (Figure A-4) shows that the pan coefficient for the BoM class A pan at Deniliquin is 0.72.

Examination of Figure A-4 shows a deviation from the straight line at high evaporation rates. Bias towards overestimation by $E_{pan}$ at high evaporation rates has also been observed at Griffith (Meyer, et al. 1999) and is considered characteristic of semi-arid environments in summer when high air temperatures for long periods elevate water temperatures in the pan and increase evaporation rates. A slightly better fit to the data was provided by using a power function and the result is shown below in Figure A-5. Although there is only a 1% improvement in $R^2$, the standard error of the estimate falls from 0.425 for the linear model to 0.355 for the power function.

\(^1\) http://www.kimberly.uidaho.edu/water/fao56/
Figure A-4. The relationship between the 11 day mean $ET_o$ at Deniliquin, calculated from the FAO Penman-Monteith equation (Allen, et al. 1998) using data from the period Feb 1998 to May 2003, plotted against 11 day mean $E_{\text{pan}}$ from the Bureau of Meteorology’s Class A pan at Deniliquin for the same period. The line of best fit is: $ET_o = 0.72 \times E_{\text{pan}}$ ($R^2 = 0.97$, $P < 0.001$, $n = 1721$).

Figure A-5. The relationship between the 11 day mean $ET_o$ at Deniliquin, calculated from the FAO Penman-Monteith equation (Allen, et al. 1998) using data from the period Feb 1998 to May 2003, plotted against 11 day mean $E_{\text{pan}}$ from the Bureau of Meteorology’s Class A pan at Deniliquin for the same period. The line of best fit is: $ET_o = 0.88 \times (E_{\text{pan}})^{0.91}$ ($R^2 = 0.98$, $P < 0.001$, $n = 1721$).
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