Tactical Irrigation Strategies for Maximising Farm Profitability in Mixed Cropping Enterprises

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Executive Summary

This report formed the literature review for a study which examined the water requirements of wheat and canola in the irrigation districts of the NSW Central Murray valley. The need for this work arose from the increasing scarcity and price of irrigation water in these districts following government water reforms, since 1995, and prolonged drought between 2002 and 2010.

For farmers to adapt to these changes, it has often been considered that the most appropriate objective for them is to improve their water productivity (WP). However, the primary goal of the farm business is to maximise profit, not WP per se, and these two goals are not necessarily coincident. In order to find the economic maximum, knowledge of the relationship between yield and water use (i.e. the production function) is required. This was examined and generalised information obtained. It was found that, in semi-arid and mediterranean type climates, improving the production functions of winter crops, rather than summer crops, will provide farmers with a greater opportunity for maintaining farm profitability when water is limited. It was also found that, if water is limiting, profits will be maximised by irrigating the crop with the greatest response to irrigation. The actual irrigation depth applied will depend on commodity prices and the relevant costs of production.

The irrigated farming systems of the NSW Central Murray valley were examined in light of these generalised findings. It was concluded that deficit irrigation of the two major winter crops grown in the valley (i.e. wheat and canola) was a viable strategy, but that further information was required to determine the profit maximising levels of irrigation for these two crops. In particular, the following information gaps were 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 were not available;

- No published local production functions were found for canola; and

- No published studies were found which examined deep percolation losses under irrigated canola.
(These information gaps were subsequently investigated and a report of the findings published: North S.H.S. (2007) “A comparison of wheat and canola water use requirements and the effect of spring irrigation on crop yields in the Murray valley.” Thesis (MAppSci). Charles Sturt University.)
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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 per cent of agricultural land NLWRA (National Land & Water Resources Assessment, 2002) and directly and indirectly contributes an estimated $12.4 billion to the Australian economy (2.3 per cent of GDP). Approximately two thirds of Australia’s irrigated agricultural production occurs in the Murray Darling Basin (MDB) and accounts for 70 per cent 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 until they were capped (“The Cap”) in 1995 (Murray-Darling Basin Commission (MDBC), 1999). A prolonged dry period and record drought, between 2001 and 2009, has seen further policy change, with diversions being actively reduced so that by 2010, roughly 1030 gigalitres (GL) of irrigation water had been “bought back” from irrigators and re-allocated to the environment (Murray-Darling Basin Authority, 2010; Productivity Commission, 2010). In addition to these measures, Australian governments introduced market forces to the water industry in 1994 to increase economic returns from the water resources of the Basin. They did this by establishing property rights to water, creating mechanisms for trade, and charging prices for water which reflect its cost of delivery (High Level Steering Group on Water, 2000).

Because of these changes to policy (and climate), irrigation farmers in the MDB face increasing competition in a market for a diminishing resource at a time when delivery costs are increasing. The bulk of the impact of these changes was predicted to 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 (MDBC), 2004). To a certain extent, this has happened. However, this prediction fails to take into account the intellectual, social and economic capital invested – both on and off farm – in major industries like dairy and rice, and the costs associated with writing this capital off. Thus, the majority of irrigators in the Central Murray valley have remained in these industries and the question they face is how to remain profitable and stay in business as irrigation water becomes less available and more expensive. This question is examined in this report with respect to one of these industries: rice based cropping enterprises in the NSW Central Murray.
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 & Nix, 1970).

Five main soil groups are recognised in the NSW Central 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 1930s 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 per cent compared to almost 100 per cent for Murray Valley irrigators in South Australia and 96 to 98 per cent 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 per cent of the area developed for irrigation, yet it consumes on average 55 to 60 per cent of the water supplied to the district. Twenty per cent of total supply is used on pastures and 11 per cent on winter crops, principally cereals (Murray Irrigation Limited, 2003). Surface application of irrigation dominates in the district, with 50 per cent of the developed area laid out to border check, 46 per cent to basin systems, 2 per cent to furrow and 2 per cent 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 that predominate in the NSW Central Murray irrigation districts have developed 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 Central Murray irrigation districts 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.
2. 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). However, the definition of WUE varies with the discipline studied and the scale of the process being measured.

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 “evapo-transpiration 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 the ratio of water used “productively” to that supplied and is dimensionless (Doorenbos & Pruitt, 1977).

A number of authors (e.g. Stanhill, 1986; Oweis et al., 1999; Barrett Purcell & Associates, 1999; Meyer, 2005) point out that the term “efficiency” should only be applied to an efficiency ratio (i.e. a dimensionless ratio). Whilst \(T_e\) and \(ET_e\) are not dimensionless, they are accepted terms and their nomenclature is retained here.

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:

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

This is similar to Howell, 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 (\(I_a\)) (\(DS = \) change in soil moisture content of the root zone). Oweis et al., 1999) include monetary as well as physical terms in the ratio, so WP can have either the units kg ML\(^{-1}\) or \$ ML\(^{-1}\). Howell, 2001) reported two definitions by Bos, 1980; Bos, 1985): the yield:ET ratio and the yield:water supply ratio. In this study these are called the “evapotranspiration WP” (\(ET_{WP}\)) and the “irrigation WP” (\(I_{WP}\)): 
\[ ET_{WP} = \frac{(Y_i - Y_d)}{(ET_i - ET_d)} \]  

Equation 2

\[ I_{WP} = \frac{(Y_i - Y_d)}{I_a} \]  

Equation 3

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

Improving WP is often seen as the most appropriate objective for farmers to follow (e.g. CRC Irrigation Futures, 2004; Department of Prime Minister & Cabinet, 2005). However, the primary goal of the farm business is to maximise profit, not WP per se, and these two goals are not necessarily coincident (Tanner & Sinclair, 1983; Vaux & 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.
3. Farmers Responsibility for Natural Resources

3.1. 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 & Kassam, 1979; Barrett & Skogerboe, 1980; Vaux & Pruitt, 1983; Howell, 1990; Oweis et al., 1999). If applied water (WA) is used, the relationship between Y and WA (i.e. the crop production function) is a diminishing-return function (Figure 1). It is generally accepted to be a second degree polynomial (Stewart & Hagan, 1973; Vaux & Pruitt, 1983; Zhang & Oweis, 1999; Zhang et al., 2000; Huang et al., 2004), though Martin 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:

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

Equation 4

They demonstrated the stability of their crop-specific constant ($k$) for crops with a leaf area index (LAI) > 3 and concluded that, while 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).

In Figure 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 1) as being equal to the soil $E$ fraction of total crop ET (e.g. Hanks et al., 1969, Tanner & Sinclair, 1983; French & 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 LAI ≈ 1 and after 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.

![Diagram of crop production function](image.png)

**Figure 1.** A generalised crop production function showing the relationship between yield (Y), evapotranspiration (ET) and irrigation (Ia).

Note: Takes into account contributions from available soil water (ASW) and rainfall (P) during a season (Source: Stewart & Hagan, 1973).

A substantial body of work supports the hypothesis that the Y–ET relationship is linear (Stewart & Hagan, 1973; Fischer, 1979; Vaux & Pruitt, 1983; Morizet et al., 1984; Steiner et al., 1985; Stanhill, 1986; Zhang & Oweis, 1999; Huang et al., 2004) and it is apparent that Te defines the upper limit for improving ET_e (e.g. French & Schultz, 1984a). However, there is debate about the constancy of Te and the Y - ET relationship, as it exhibits considerable variability between sites, within and between species and between years/seasons (Vaux & 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-ET relationships using relative values (e.g. Doorenbos & Kassam, 1979). While 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 occurred (Kirda, 2000).

Stewart and Hagan (1973) explained the convex nature of the Y – Wa relationship by plotting Y against both ET and Wa 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 Wa increased. They attributed the divergence to non-ET losses (i.e. deep
percolation, runoff and changes in soil water content) and argued that if I was 100 per cent (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, further increasing the subjectivity of the Y- W relationship.

Because the Y- W 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).

3.2. 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 (below) and given by:

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

Equation 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](image_url)  

**Figure 2.** Generalised revenue function showing points at which yield, profit, water productivity (WP) and irrigation WP (IWP) 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 & 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 & Hagan, 1973; Heermann et al., 1990). This was generally the case in Australia 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 & Bresler, 1983). Maximum profit can never be coincident with maximum $I_{WP}$ (Equation 3) and will only coincide with maximum yield ($Y_{max}$) if the price of water is zero (Vaux & 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).

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 in this case will be the most productive in terms of yield and therefore the most profitable. This strategy has considerable potential for increasing profits from irrigation in semi-arid regions (Stewart & Musick, 1982).

![Figure 3](image-url)  
*Figure 3.* (a) Production functions for maize at four different irrigation efficiencies (Ⅰ 100 per cent, Ⅱ 82 per cent, Ⅲ 71 per cent and Ⅳ 48 per cent) 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).
Barrett and Skogerboe (1980) disagreed with Stewart and Hagan. They reasoned that the production function would equate to a straight line Y-ET relationship when irrigation efficiency was 100 per cent and, as $I_e$ decreased, would become increasingly curvilinear (Figure 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 of $I_{max}$ also decreased so that the optimal depth was nearly the same no matter how efficient the irrigation system (Figure 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 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; and
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 and Bresler’s (1983) analysis and using a more general solution to the crop production functions (Doorenbos & Kassam, 1979; Martin et al., 1984) than the earlier, experimentally derived relationships. They showed that Barrett and 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 and Bresler’s four agro-economic rules were expressed in equation form by English and Raja (1996) for a quadratic production function of the form:
\[ R(W_A) = P_c f(W_A) = P_c \left( a_0 + a_1 W_A + a_2 W_A^2 \right) \]  \hspace{1cm} \text{Equation 6}

and a linear cost function of the form
\[ c(W_A) = c_1 + c_2 W_A \]  \hspace{1cm} \text{Equation 7}

where \( c_1 \) and \( c_2 \) represent fixed and variable costs respectively. Maximum yields are attained at \( W_m \) (Figure 4, below) when the slope of the revenue function is zero:

\[ W_m = -\frac{a_1}{2a_2} \]  \hspace{1cm} \text{Equation 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 4):

\[ W_l = \frac{c_2 - P_c a_1}{2P_c a_2} \]  \hspace{1cm} \text{Equation 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 4) where the slope of \( R(W_A) \) equals the average return per unit of \( W_A \) net of fixed costs (\( c_1 \) in Figure 4).

\[ W_w = \left( \frac{P_c a_0 - c_1}{P_c a_2} \right)^{\frac{1}{2}} \]  \hspace{1cm} \text{Equation 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 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 ($W_w$).

Note: 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).

3.3. 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 & Raja, 1996).

Zhang and Oweis (1999) used English and Raja (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 to 73 per cent of the water required for full irrigation for a yield reduction of 13 per cent, while watering to achieve a target yield of 4 to 5 t ha$^{-1}$ saved 100 per cent in a wet year and 63 per cent on average for a yield reduction of 31 per cent. 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. Simulation results show the optimum strategy for wheat in northern China is similar (Zhang et al., 2000).

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 per cent 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 per cent. Increasing the price and/or the scarcity of water significantly increased the benefits of deficit irrigation over the full irrigation strategy.

When water supply is limiting and/or the water price is high (relative to crop price), then deficit irrigation has been shown to provide greater profits and higher WP than full irrigation in the Murrumbidgee valley (Robinson, 2004), an area similar to the NSW Central Murray valley. 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 \( W_{ew} \) and \( W_{ew} \) in Figure 4) at which profits equalled those from full irrigation \( W_{m} \) in Figure 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 per cent for the water limited and 30 per cent 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 has been shown to be a successful strategy for wheat, but rainfall probability and soil water availability need to be taken into account (Zhang & Oweis, 1999; Zhang et al., 2000).

The 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 & 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).
4. The Role of Deficit Irrigation in the Rice Based Farming Systems of the NSW Central Murray

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

Table 1. Production data from 2000 to 2001 for the most commonly grown summer (left) and winter (right) crops in the Central Murray statistical sub-division (Source: Australian Bureau of Statistics, 2001).

<table>
<thead>
<tr>
<th>Summer Crops</th>
<th>Area (ha)</th>
<th>Production (t)</th>
<th>Average Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rice</td>
<td>90,672</td>
<td>836,048</td>
<td>9.2</td>
</tr>
<tr>
<td>soybeans</td>
<td>1,844</td>
<td>3,495</td>
<td>1.9</td>
</tr>
<tr>
<td>maize grain</td>
<td>947</td>
<td>9,164</td>
<td>9.7</td>
</tr>
<tr>
<td>millet</td>
<td>522</td>
<td>809</td>
<td>1.5</td>
</tr>
<tr>
<td>sorghum</td>
<td>259</td>
<td>875</td>
<td>3.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Winter Crops</th>
<th>Area (ha)</th>
<th>Production (t)</th>
<th>Average Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wheat</td>
<td>226,434</td>
<td>639,257</td>
<td>2.8</td>
</tr>
<tr>
<td>barley</td>
<td>84,790</td>
<td>195,900</td>
<td>2.3</td>
</tr>
<tr>
<td>canola</td>
<td>44,405</td>
<td>65,159</td>
<td>1.5</td>
</tr>
<tr>
<td>triticale</td>
<td>10,481</td>
<td>27,281</td>
<td>2.6</td>
</tr>
<tr>
<td>oats</td>
<td>8,212</td>
<td>16,384</td>
<td>2.0</td>
</tr>
<tr>
<td>field peas</td>
<td>5,781</td>
<td>4,421</td>
<td>0.8</td>
</tr>
<tr>
<td>lupins</td>
<td>1,804</td>
<td>2,674</td>
<td>1.5</td>
</tr>
<tr>
<td>faba beans</td>
<td>734</td>
<td>1,307</td>
<td>1.8</td>
</tr>
<tr>
<td>chick peas</td>
<td>381</td>
<td>470</td>
<td>1.2</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 (12-16 ML ha$^{-1}$). The crop requires ponded conditions for 120 to 170 days (October to March) 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., 2002b). Intermittent irrigation until two weeks before panicle initiation can reduce water use by 18 to 25 per cent 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 per cent and 100 per cent, 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 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).

4.1. 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 & Oweis, 1999; Oweis et al., 1999). It is also the crop most commonly grown in rotation with rice (Table 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 (Australian Bureau of Agricultural and Resource Economics, 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 & Chase, 1992; Stapper & Fischer, 1990a). The difference between
the average and maximum yields suggests there is potential to increase irrigated wheat yields provided favourable soil conditions.

4.2. The Role of Canola

Canola is the most significant of all the broadleaf winter crops grown in the NSW Central Murray (Table 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 & Marcellos, 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 per cent 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). This 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 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\(^{-1}\) (Australian Bureau of Agricultural and Resource Economics, 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 and Smith, 1992).
5. 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:

\[ GDD = \sum_{S_{1}}^{S_{2}} (T_{m} - b_{o}) \]  

Equation 11

where \( T_{m} \) is mean daily temperature, \( b_{o} \) is the base temperature and \( S_{1} \) and \( S_{2} \) are two development stages.

5.1. 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° or 4°C are commonly used as the base temperature for physiological processes in wheat, while the optimum temperature for growth is 20 to 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 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 and Rawson’s conclusions, believing the apparent complexity was a product of the phenological framework 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 four 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.

5.2. 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 & 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 four 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 & 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 and Makepeace, 1984).

The period from 50 per cent flowering to physiological maturity was not examined by Robertson et al. (2002) but is also determined solely by temperature (Mendham & 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).
6. 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:

$$ET_c = ET_o \times K_c = (E_{pan} \times K_p) \times K_c \quad \text{Equation 12}$$

Empiricisms in the different relationships used to estimate net radiation and calculate the wind function in $ET_o$ equations can produce a 23 per cent 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).

Lysimeter studies at Griffith were used to develop a locally calibrated Penman combination equation (“Penman-Myer”) (Meyer, 1999; Meyer et al., 1999). Comparisons showed a strong correlation between Penman-Meyer $ET_o$ and both $E_{pan}$ and Penman-Monteith $ET_o$, but with $E_{pan}$ about 7 to 8 per cent higher (up to 30 per cent higher when evaporation $>10$ mm/day) and Penman-Monteith $ET_o$ consistently lower by about 30 per cent (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 per cent.

At a national workshop in June 2002 it was proposed to adopt the Penman-Monteith equation as a standard for Australia (National Program for Irrigation Research and Development, 2002). The 24 to 30 per cent 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.
6.1. Growth Stage Length

Allen et al. (1998) defined four crop growth stages: an initial stage from sowing to 10 per cent ground cover; a crop development stage from 10 per cent 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.

6.1.1. 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 to 45° Latitude differ markedly from those estimated by Meyer et al. (1999) for spring wheat sown on the May 15 at Griffith and grown under average temperatures (Table 2).

<table>
<thead>
<tr>
<th>Source</th>
<th>Initial</th>
<th>Development</th>
<th>Mid-season</th>
<th>Late Season</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allen (35-45° Latitude)</td>
<td>20</td>
<td>25</td>
<td>60</td>
<td>30</td>
<td>135</td>
</tr>
<tr>
<td>Meyer (Griffith, NSW)</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 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. (1999) results agree with Hedditch (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 (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.

6.1.2. 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 May 5 sowing and a linear increase in \( K_c \) from
emergence to LAI >3 (Edraki, M. 2001, pers. comm.). While 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.

6.2. Crop Factors ($K_c$)

6.2.1. Wheat

$K_c$ values for irrigated wheat from a number of sources are shown Table 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 to 30 per cent 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 & Gibbs, 1997; Hughes, 1999; Giblin & Lacy, 2003). All of them recommend their $K_c$ values be used with Penman- Meyer $E_{To}$ from the CSIRO weather station network in southern NSW for calculating $ET_c$.

Table 3. Published crop coefficients for irrigated spring wheat for use with either the Penman-Monteith (Sources: Allen et al., 1998; Penman-MeyerMeyer, 1999) $E_{To}$ equations.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>Crop Growth Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_c$ for use with Penman-Monteith $E_{To}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keefer, 1977)</td>
<td>Emerald, Qld</td>
<td>0.25 1.13 0.4</td>
</tr>
<tr>
<td>Cooper, 1987)</td>
<td>Trangie, NSW</td>
<td>0.3 1.25 0.3</td>
</tr>
<tr>
<td>Allen et al., 1998)</td>
<td>universal</td>
<td>0.3 1.15 0.25</td>
</tr>
<tr>
<td>$K_c$ for use with Penman-Meyer $E_{To}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meyer et al., 1999)</td>
<td>Griffith, NSW</td>
<td>0.3 1.05 0.4</td>
</tr>
<tr>
<td>Smith and Gibbs, 1997); Hughes, 1999)</td>
<td>Murray Valley</td>
<td>0.3 1.0 0.6</td>
</tr>
</tbody>
</table>

1. Keefer, 1977) crop coefficients were converted from values for use with $E_{pan}$ data using a $K_p$ of 0.8.

6.2.2. Canola

$K_c$ values for canola for use with Penman-Monteith $E_{To}$ are given as 0.35 for the initial stage, 1.0 to 1.15¹ 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 $K_c$ for rapeseed of 0.75 for use with $E_{pan}$ data in northern NSW.

¹ the lower value is for rainfed crops having less dense plant populations
This equates to a $K_c$ of 0.94 for use with Penman-Monteith $ET_o$, provided $K_p$ is 0.8. Smith and Gibbs (1997) and Hughes (1999) give $K_c$ values for canola and Penman-Meyer $ET_o$ in the Murray Valley (Table 4) but don’t describe how these values were obtained. The $K_c$ values for canola used in CSIRO’s SIRAG-PC program are lower (Table 4), but it is acknowledged that these are “educated guesses” (Edraki, M. 2001, pers. comm.).

Table 4. Crop factors for canola in the Murray Valley (Sources: Hughes 1999; Giblin & Lacy 2003; Smith & Gibbs 1997) and at Griffith (Edraki, M. 2001, pers. comm.) for use with Penman-Meyer $ET_o$.

<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.
7. **Irrigation Management**

7.1. **Autumn Pre-irrigation**

In the Central Murray valley, pre-irrigation of winter crops in autumn is recommended for paddocks with less than 50 per cent 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 per cent of years (Fisher, 2002), though 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).

7.2. **Spring Irrigation**

7.2.1. **Wheat**

The management of irrigated wheat is well described in a number of reviews (Robins et al., 1967; Doorenbos & Kassam, 1979; Musick & Porter, 1990; 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; Stapper & Fischer, 1990b; Stapper & Fischer, 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 & 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 $>6.0 \text{ t ha}^{-1}$ 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; and

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

Full irrigation with 3-5 spring irrigations to achieve $>6.0 \text{ t ha}^{-1}$ 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 $0.9 \text{ t ha}^{-1}$, so the preferred strategy is to target yields of $5.0 \text{ t ha}^{-1}$ (Lacy & Thomas, 2001).

### 7.2.2. Canola

The $K_c$ values for canola in Table 4 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 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 canola water requirements are different to wheat, whereas Queensland Department of Primary Industries and Fisheries (2005) state 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 et al., 1984), while one and three 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 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 $B. napus$ 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 & Thurling, 1978a). In all these examples, crops were not water stressed until after flowering and pods per m$^2$ was the main yield component which contributed to the response to irrigation.

While there appears to be a yield advantage from watering to avoid moisture stress after flowering, Richards and Thurling, 1978a) found 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 pre-dawn 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 two to three weeks later.

Colton and Sykes (1992) advise 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 canola required irrigating in spring earlier than wheat and recommended the first irrigation be timed when plant available water (PAW) was at 60 per cent (compared to 50 per cent 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 three to four spring irrigations (4 to 5.5 ML ha\(^{-1}\)). In more normal seasons, growers were expected to irrigate two to three 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 per cent 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 similar reasons as applied to wheat, full irrigation (3-5 spring irrigations to achieve 3.5 t canola grain 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.
8. Critical Growth Stages

8.1. 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 & Kassam, 1979). In the Murrumbidgee Irrigation Area, moisture stress (i.e. PAW < 50 per cent) during spike emergence and flowering reduced yield from 7.0 to 3.3 t ha\(^{-1}\) through reductions in spikes m\(^{-2}\) (37 per cent), individual grain weight (15 per cent) and grain number per spike (13 per cent), whereas stress during grain filling only reduced yield by 20 per cent, mainly through a 16 per cent reduction in individual grain weight (Thompson & Chase, 1992).

Zhang and 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.

8.2. Canola

Opinions differ as to the most drought sensitive stage in canola. Bramm (1981) showed that the critical growth stage of rapeseed, with its highest water requirement, was the period between flowering and ‘green maturity’. Richards and 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 per cent due seed abortion and a reduction in the number of pods per plant. Jensen et al. (1996) found 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). This is supported by the finding that the retention of many seeds per pod is the key factor to achieving high yields (Mendham et al., 1984). Mailer and Cornish (1987) also found 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 m².

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).
9. Production Functions and Deficit Irrigation

9.1. 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 fully satisfy irrigation requirements, can thus be recommended in semi-arid regions where rainfall is a significant contributor to crop water requirements (Stewart & Musick, 1982; Oweis & Ryan, 1998; Oweis et al., 1999; 2000; Wang et al., 2001). However, this strategy requires an understanding of the relationship between $Y$ and $WA$ and both linear and curvilinear responses have been reported (Musick & Porter, 1990).

French and Schultz (1984a; 1984b) assumed 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 5). From this he concluded that the optimum irrigation frequency lay between three and seven 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 is 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 and 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 and Chase (1992).

Zhang and 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 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 5 shows that Zhang and Oweis’ (1999) production function is quite similar to Cooper, 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 5. Wheat grain yield as a function of total applied water from published studies.](image-url)
9.2. 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 and 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 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 & Fernandez, 1978). Clarke and 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 two irrigations and 0.9 t ha$^{-1}$ between two and five irrigations. Their dryland yields were considerably lower than Munoz and Fernandez’s, so there was greater potential for them to increase yields to around the 3 t ha$^{-1}$ level achieved by Munoz and 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 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 6. Canola yield and water use data from published studies in which various levels of irrigation were applied.
10. Wheat and Canola Comparative Experiments

10.1. 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 the finding that 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 (Holland et al., 1999).

10.2. 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 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 and Sudmeyer (1993) used the ventilated chamber technique to estimate seasonal \(ET_c\) 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; Dreccher 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 are 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 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.

10.3. 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 per cent 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 & 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 & Zeiger, 1991).
Zhang et al., 2004) observed that waterlogging during the vegetative phase in 2002 reduced shoot biomass by 27 per cent and 40 per cent in wheat and canola respectively compared to 2001, which was drier. Despite suffering a greater reduction in biomass, canola yields were 17 per cent higher in 2002 whereas wheat yields were 37 per cent 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 per cent increase in grain size.

10.4. Root Distributions and Depths of Water Extraction

Weiss (1983) and Colton and 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 three of the four 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 use 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 to 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 and Kirkegaard (1995) finding of a lack of evidence for “biological drilling” by canola in the B-horizon of dense, duplex soils. However, Rao and 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 and Goulburn loam) with a shallow clay loam A horizon overlying a structure-less, massive clay B horizon.

Richards and Thurling (1978a) observed 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; 1968). The negative association between yield and root/shoot ratio in their second paper (Richards & 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.
11. 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 (Talsma, 1963, Loveday & Scotter, 1966, Loveday et al., 1978, Muirhead, 1978; 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 per cent 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 per cent of daily $ET_c$ from a wheat crop, even though deep percolation was 49 to 81 mm over the whole season when irrigating at 50 to 75 per cent 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;2003b) 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. (2003a) found no published work that examined deep percolation below canola crops.
12. Conclusions

The impact of increasing competition for finite water resources in the MDB is expected to be greatest upon farmers in the Central 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 none of the field data sets he used, which included wheat, incorporated yield responses to various levels of water deficit. This overlooking of Cooper (1980b) results, as well as the scepticism by Steiner et al. (1985), indicates they need verifying for the southern MDB.

Deficit irrigation is a recommended practice for both wheat and canola in the Central 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. While 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 Central 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 review of the literature 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 and Fischer (1990a) wheat model and Robertson et al. (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.
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